INVESTIGACIÓN

# Reduciendo la huella de carbono proveniente de la congestión vial en el área metropolitana de San José, Costa Rica

# Reducing Carbon Footprint from Traffic Congestion in the Metropolitan Area of San Jose, Costa Rica

**Ricardo Del Valle Hernández [1], Edwin Gerardo Acuña Acuña [2]**

Fecha de recepción: 5-06-2024 | Fecha de aprobación: 6-07-2024
DOI: 10.63058rhombus.v4i2.229

## Resumen

Esta investigación tiene como propósito establecer la relación entre la producción de gases de efecto invernadero y la congestión en el área metropolitana de Costa Rica. Para lograrlo, se empleó una metodología inspirada en el Informe de la Nación 2018 del Programa Estado de la Nación. En esta, se aplicó una encuesta digital a una muestra de aproximadamente 6000 individuos, específicamente, estudiantes universitarios de 18-24 años que residen en el Gran Área Metropolitana. Para el análisis, se utilizaron herramientas como Microsoft Excel, Google Maps, My Maps, Komoot, Datawrapper y Microsoft Forms. Asimismo, es importante reconocer las limitaciones de este enfoque, ya que la muestra se seleccionó de manera no aleatoria, lo que limita la heterogeneidad. Además, la disponibilidad de direcciones de correo electrónico del universo muestral fue un desafío. No obstante, los resultados de este estudio podrían tener un impacto significativo en la forma en que se evalúa el inventario de gases de efecto invernadero a nivel nacional, promoviendo su uso como un indicador de tendencias a partir del Casco Metropolitano en lugar de un indicador per cápita. Además, la segmentación geográfica ofrece un enfoque novedoso que puede guiar a acciones específicas del Ministerio de Ambiente y Energía para abordar la contribución de distintas regiones al indicador de carbono neutro.

## Palabras clave:

Ciudad inteligente, GEI, huella de carbono, movilización, PIMUS.

1 Máster en Administración de Negocios con énfasis en Administración de la Tecnología, Universidad Latinoamericana de Ciencia y Tecnología (ULACIT), ORCID: 0000-0002-4861-9107, correo electrónico: rick_delvalle@hotmail.com

2 Doctor en Matemática y Física en Universidad de Salamanca (España), Universidad Latinoamericana de Ciencia y Tecnología (ULACIT), ORCID: 0000-0001-7897-4137, correo electrónico: edwacuac@gmail.com

## Abstract

The purpose of this research is to establish the relationship between greenhouse gas production and congestion in the metropolitan area of Costa Rica. To achieve this, a methodology inspired by the 2018 State of the Nation Report from the State of the Nation Program was employed. A digital survey was administered to a sample of approximately 6,000 individuals, specifically university students aged 18-24 residing in the Greater Metropolitan Area. Tools such as Microsoft Excel, Google Maps, My Maps, Komoot, Datawrapper, and Microsoft Forms were used for analysis. It is important to acknowledge the limitations of this approach, as the sample was non-randomly selected, limiting heterogeneity. Additionally, the availability of email addresses within the sample population posed a challenge. Nevertheless, the findings of this study could have a significant impact on the way national greenhouse gas inventories are assessed, promoting their use as a trend indicator based on the Metropolitan Area rather than a per capita indicator. Furthermore, the geographical segmentation offers a new approach that can guide specific actions by the Ministry of Environment and Energy to address the contribution of different regions to the carbon-neutral indicator.

## Keywords:

Carbon footprint, GHG, mobilization, PIMUS, smart city.

## Introduction

According to AC&A Global and Gensler (2017), "density, diversity, and design are variables commonly used to determine how sustainable and attractive a city is" (p. 12). The Metropolitan Area of San Jose (AMSJ) exhibits a population density of fewer than 4,000 inhabitants per square kilometer, an intense traffic resulting from geographical polarization in employment opportunities, and an inadequate and incongruous mobility network concerning user needs.

However, another perspective on the AMSJ situation, compared to other areas, is offered by Pérez et al. in their article "Intelligent Mobility" (2015), where it says that "Despite the significant benefits of agglomeration economies, cities also face problems that are hard to solve, many of which are associated with mobility: pollution, climate change, traffic congestion, urban sprawl, etc." (p. 132).

Additionally, the World Health Organization (WHO), along with various studies, points out that cardiovascular and respiratory systems are the primary systems affected due to particulate matter concentration, leading to increased medication use, mortality, and chronic health issues (WHO, 2000 and 2006). Therefore, the National University of Costa Rica monitored air quality in the country in 2016. The results of this study for the nine designated sites showed that the annual average was more than doubled during the data collection period (µg/m3). By 2025, according to projections presented in Chapter 6 of the State of the Nation report 2018, the amount of pollutant gases from the vehicle fleet (cars, motorcycles, transportation) could reach 8,000 gigagrams of carbon equivalent.

Moreover, the impact of mobility can be classified into seven major groups: 1) socio-environmental impacts, 2) greenhouse gas emissions, 3) air quality, 4) noise, 5) socio-economic impacts, 6) accidents, and 7) traffic congestion (AC&A Global and Gensler, 2017). The cost of these externalities was estimated at over 2.8 billion US dollars, and 7% of this cost is related to greenhouse gas emissions, air quality, and traffic congestion.

Now, importing best practices from leading countries in urban and functional development can have an effect on some of the major impact areas of mobility, understanding that there is limited room for improvement in terms of buildings in the Costa Rican context. However, the concept of smart cities can provide some tools and theoretical frameworks to apply regarding traffic congestion and its consequences. Wade and Pfäffli (2016) define "Smart Cities" as urban areas that have capitalized on the efficiency of service provision (electricity, road networks, security, water, commerce, and others) using digital technologies to be more environmentally friendly and socially inclusive. The goal of a smart city is to enhance its appeal to citizens or the commercial/industrial sector by enhancing or adding services. Under this concept, a service can be anything offered to citizens or businesses, such as lighting, traffic management, parking, electricity, water, communications, and others. Nevertheless, improvement through technology (efficiency, robustness, accessibility, availability, cost) is what differentiates a common city from a smart city (Machado, Qu, Cervantes. 2019).

The conceptualization of the smart city for the AMSJ can bring significant challenges at the political, economic, social, and even public safety levels. However, the scope of this research is limited to the application of tools used in other countries to improve automotive mobility. Although there are technologies applicable to the design and improvement of mobility, regulations, legislation, socio-cultural attitudes, and commercial interests can hinder the diffusion and adoption of lower-impact options in terms of pollutant gas generation. Therefore, it is important to reconcile the positions derived from research with industrial and residential planning. As the transition to sustainability takes time, it is also necessary for policy to strike a balance between long-term objectives and immediate actions.

Successful experiences in other countries that have implemented intelligent designs for their cities show that a combination of hard data and surveys helps understand the degree of influence that technology provides in addressing challenges in the pursuit of improving the quality of life for residents (Lanvin, 2023). On one hand, Operations Research is the discipline that aligns most with this type of analysis, given its ability to model complex and large problems (in terms of variables) using mathematics, computational power, and, depending on resources, machine learning automation mechanisms to predict outcomes in dynamic scenarios (Taha, 2012). On the other hand, studies that focus more on traffic flow through the rearrangement of traffic lights in cities (quantity, placement, timing) use heuristic models like ACO (Ant Colony Optimization) to minimize travel time, achieving significant improvements for travel times between avenues (Yi, Fazhi, Nemg, Yimin. 2018). Nevertheless, to date, there is no research that relates these variables within a specific population, such as students, based in Costa Rica or elsewhere.

There are studies conducted by PEN (State of the Nation Program) in Chapter 6 of the 2018 report used data from the WAZE application to locate the most congested points and bottlenecks in the area of interest. However, the road map has changed since then, as some of the ongoing projects were completed between 2022 and 2023 (Uruca underpass, Tibás-La Uruca viaduct). Since then, no further monitoring has been conducted on the impact of bottlenecks in the San Jose Metropolitan Area.

This research uses the logic of the PEN study but from an individual-mobility perspective to illustrate the routes with the highest demand in a student population concentrated at one point (campus). The interest of this research is to experimentally determine the travel habits between individuals' residences, study locations, and workplaces, as well as calculate the potential improvement in air quality through road network improvements in the San Jose Metropolitan Area.

## Research Questions

In the context of the Metropolitan Area of San Jose, Costa Rica, we face critical challenges related to traffic congestion and air quality. In this research, we will address two essential questions with the primary objective of seeking solutions to these issues. On one hand, the first research question focuses on the possibility of reducing greenhouse gas emissions generated: ¿Is it possible to achieve an important reduction in greenhouse emissions generated by traffic congestion to meet the ambitious goals of Climate Neutrality by 2050? On the other hand, the second research question aims to identify effective strategies to improve air quality in the Metropolitan Area of San Jose: ¿Can successful practices associated with smart cities and the redesign of urban traffic be implemented as potential solutions? Additionally, we will explore how improvements in the road network can potentially impact air quality and carbon footprint reduction, especially for the student population.

These research questions serve as fundamental pillars to progress towards a more sustainable future and fulfill the commitments of climate neutrality by 2050. Solving these challenges will not only benefit the urban environment and the environment itself, but also enhance the quality of life for the residents of the Metropolitan Area of San Jose. Therefore, this research is intended to answer these questions to achieve the research objectives and promote positive change in the region.

## General Objective

The objective of this research is to comprehensively identify and analyze the factors influencing greenhouse gas production, taking into account the mobility patterns of the student population of a university in the Metropolitan Area of San Jose, Costa Rica.

This investigation aims to provide a detailed understanding of how students' daily commutes, whether from their homes to the university campus or other destinations, contribute to greenhouse gas emissions. Additionally, we aim to examine the influence of various variables, such as transportation mode, distance traveled, travel times, and other mobility-related factors, to provide valuable insights for the design of strategies and policies that reduce the carbon footprint associated with these activities. Ultimately, this research aims to contribute to the mitigation of climate change in the urban environment of San Jose.

## Specific Objectives

- Analyze and characterize the mobility patterns of the student population by collecting data through voluntary participation surveys, and considering variables such as transportation modes, distances traveled, and travel times.

- Evaluate and compare greenhouse gas emissions and estimated costs associated with these emissions in 2017 with current results to determine variations and trends over time.
- Assess Costa Rica's progress toward meeting its 2050 commitments in terms of greenhouse gas emissions reduction, considering actions and measures implemented at the local level.
- Identify and analyze improvements in traffic congestion resulting from changes in the road network of the Metropolitan Area of San Jose, focusing on the aspects that have contributed to congestion reduction and urban mobility enhancement.

## Literature Review

Taking into account what have been said about the topic, we can analyze the following documents. Firstly, the following quote explains that

> Large cities struggle daily with the serious problem of vehicular congestion and its effects such as environmental pollution, vehicle wear due to constant acceleration and braking, delays, and prolonged waiting hours. These effects lead to a decrease in the quality of life due to stress problems faced by drivers and pedestrians when moving through different cities. Reduction in productivity is another consequence due to the time lost on the way to workplaces (Carballo, Villagra, and Erredecalde, 2019).

Moreover, the global situation regarding road traffic has exceeded pre-pandemic levels, reporting transit time increases of up to 49% (as in the case of Chicago, USA), as well as a decrease of up to 1% (as in the case of Paris, France), in relation to measurements from 2021 (Pishue, 2022).

According to the information provided in the State of the Nation Program in 2018, in its chapter 6, this information aligns with what was described by Villagra and Erredecalde and the INRIX report (Traffic Scorecard 2022): "For the working population, the economic costs derived from congestion in the GAM represent around 3.8% of the GDP" (Barrantes, 2018). Therefore, vehicular congestion has negative effects on various aspects of users' routines in cities, including commercial, educational, and health sectors. Likewise, Villagra and Erredecalde, describe the effect of gases related to the carbon footprint in Costa Rica.

From the chemical effect of internal combustion in engines, gases are produced. These can be classified into two types: harmless and pollutants. Harmless gases include Nitrogen, Oxygen, Carbon Dioxide, Hydrogen, and water vapor. Pollutants are formed by Carbon Monoxide, Hydrocarbons, Nitrogen Oxides, and particulate matter. On one hand, carbon dioxide (CO2) is a product resulting from the combustion of materials containing carbon (gasoline or diesel). Despite being a non-toxic gas, CO2 has direct effects on the atmospheric layer, contributing to global warming, a consequence of the greenhouse effect (Poudenx, 2008). On the other hand, carbon monoxide (CO) is produced due to the incomplete combustion of carbon mass in engine chambers. It has defined characteristics, such as colorless, odorless, explosive, and highly toxic. Physiologically, it hinders the transport of oxygen during blood circulation.

Additionally, other combustion-derived gases are nitrogen oxides (NOx), resulting from the combination of nitrogen and oxygen (NO, NO2, N2O). The theoretical explanation for these gases involves the relationship between high pressure, high temperature, and excess oxygen during combustion in the engine.

Nitrogen monoxide (NO), another combustion-derived gas, is a colorless, odorless, and tasteless gas. However, when combined with ambient air, it transforms into nitrogen dioxide (NO2) - reddish, pungent odor, irritates the nose, throat, and lungs.

In addition, hydrocarbons, like particulate matter, result from a process of incomplete combustion, mainly from diesel engines, and manifest as soot or ashes. The major contributor is the transportation sector.

Above all, the positive, as well as negative effects of the trend in road network density, must be considered in urban planning. For example, healthcare facilities must consider road systems to support emergency treatment. Architecturally, reducing the frontal area of buildings increases wind speed, leading to better distribution of air pollutants in the city, using the principles of cross-ventilation (Wang, Cheng, Sun et al, 2019). Studies with broader geographic coverage, such as the one conducted by Liu, Men, Tan et al. (2022) in China, which studied 253 cities, indicate that road network management, peripheral urban planning, and the commercial core of cities have significant impacts on air quality and the carbon footprint associated with major gas emitters (manufacturing and transportation).

Furthermore, the US National Oceanic and Atmospheric Administration indicated that greenhouse gas pollution - globally - prevented heat dissipation by 49% in 2021, compared to 1990 (NOAA, 2023).

On the other hand, the importance of urban planning based on higher flows (speed or movement density) is one of the conclusions reached by researchers like Kitpo, Kugai, Inoue et al., from their study "Internet of Things for Greenhouse Monitoring System Using Deep Learning and Bot Notification Services" (2019). Greenhouse gas production is proportional to the degree of mobility in cities, according to the Smart Cities index published by IMD - International Institute for Management Development- in 2023. This aligns with the criteria of the State of the Nation Program, in its chapter 6, which holds responsible the entities in charge of urban planning for following or encouraging linear, dispersed, and low-density cities, which increase traffic, becoming an unsustainable pattern since its last publication (2013).

Therefore, the magnitude of the carbon footprint is directly associated with vehicular density. It is also combined with the effects of the vehicular density in cities that do not mitigate the effects of obsolete urban planning or apply prohibitive measures to contain greenhouse gas production, without addressing the growth of the automotive fleet, traffic efficiency, or rationality of design in road structure (Ashhad, Cabrera, and Roa, 2020).

According to the American National Standards Institute (ANSI), the ISO/IEC 30182:2017 standard contains the design framework for smart cities. This standard provides guidelines to align business objectives and service provisioning to cities in a way that adjusts urban expansion, and avoids the invasion of environmentally sensitive areas and agricultural areas unsuitable for development, such as the pressure exerted on land and natural resources when urbanizing enhances the emission of greenhouse gases. Moreover, it also mentioned that metropolises and cities contribute 70% of greenhouse gas emissions and two-thirds of global energy consumption (Schirn, 2022).

Other studies reveal that reducing the carbon footprint generated in cities depends on policy and social decision-making (Government, citizens, and labor/commercial forces). This is called value creation from smart cities, and it is presented in the study "Smart Cities in the World, Value Creation, and Suggestion for Vietnam" (Hương, Lam, and Vuong, 2023).

However, within the consulted literature, there is no unanimity in the formula for reducing the carbon footprint produced within the city limits. The concept of a smart city has evolved from 1974 to the present, especially due to the use of more holistic approaches, where the role of social, economic, and institutional forces makes the goal of development drive transformative changes in urban, physical, social, and economic infrastructures (Sharifi, Allam, and Feizizadeh, 2021). For example, mitigation or compensation through the establishment of "green belts" is widely known for its rapid implementation (tree planting), based on experiences in Asian countries, specifically areas such as student campuses (Suresh, Moonra, and Tandel, 2019).

In contrast, for more western latitudes, such as Spain, efforts focus on a 35% reduction in primary energy consumption that converts the current electrical system to 100% from renewable sources. These strategies aim to reduce emissions by 20% by 2030 compared to 1990 emissions (Fueyo, 2021).

Now, the implementation of restrictive measures on mobility, such as those carried out between 2019 and 2020 in Costa Rica during the pandemic, resulted in 26% decreases within the greenhouse gas inventory recording window (National Meteorological Institute, 2020). The study conducted between June 2019 and June 2020 shows a reduction of approximately 93,000 tons of CO2, a 16% decrease in cumulative emissions (Presidency of the Republic of Costa Rica, 2022).

As you can see, various strategies can mitigate the carbon footprint, reduce greenhouse gas inventory (INGEI), or maintain the current state. However, those related to urban planning and traffic decongestion are more comprehensive in their approach and have more dynamic sustainability plans. The adoption of solutions derived from numerical methods (mathematical and computational approaches) has proven to be successful in optimizing the placement of traffic lights, identifying release routes, and pedestrian access, as well as maximizing traffic flow in smart cities (Yi, Fazhi, and Neng, 2018).

Finally, data collection within a convenience population may show similarities with experiences in other countries, such as those in Asia, South America, or Europe. Therefore, understanding movement patterns from residences to workplaces or study locations, as well as from study or work locations to residences, will provide information about preferred routes, modes of transportation, time zones, and the contribution to the carbon footprint within the metropolitan area of San Jose, Costa Rica.

## Methodology

### Methodological Approach

This research is exploratory. It employs a quantitative approach with primary information, data collection, and analysis using statistical and georeferenced methods. The methodology closely aligns with that used by the PEN in its chapter 6 of 2018 (Barrantes, 2018), as well as what was observed in the PIMUS report (AC&A, Gensler, 2017).

### Primary Data

Hernández-Sampieri and Mendoza (2018) refer to data collection as the application of one or more measurement instruments that allow gathering relevant information about the study variables in the selected sample or cases (p. 226). In this case, data was collected through an electronic form administered to the subjects comprising the sample space.

### Study Population

According to data obtained from the World Bank Group (2020), Costa Rica records a per capita CO2 production of 1.36 metric tons, which 55.3% of total emissions correspond to the Energy and Transportation sector. The university-level student population is representative because it meets the requirement of mobility from their residence to workplaces, study locations, and return to the starting point, frequently using the Metropolitan Area and various modes of transportation. The university comprises a quantity of subjects close to 78,000 for which a population sample of 6,216 was selected (for convenience). The selected individuals belong to the 18-24 years' age group, are residents of the Greater Metropolitan Area (GAM), have workplaces and study locations in the same area.

## Study Sample

The variables used to define the stratum are the attributes: university student, age between 18 and 24 years old and is a resident of the Greater Metropolitan Area. A simple random sampling method is employed on an infinite population,

**Figure 1. Sample Size formula**

$$n = \frac{N Z^2 \quad pq}{d^2 \ (N - 1) + Z^2 \quad pq}$$

Source: Sample Size Calculator. Questionpro.com

where N is the population size, Z is the statistic for margin of error and confidence level, p and q are the proportions of success/failure, and d is the level of precision. Online sample size calculators can also be used for this matter, as shown in figure 2:

**Figure 2. Sample Size Calculation**


Source: Sample Size Calculator. Questionpro.com

## Methods of Analysis

Data analysis combines statistical and geographical information (Komoot, Google Maps) through relational tables (Excel) and the representation of this through graphs (Gephi software). Additionally, Power BI was used for creating visualizations.

## Evaluation and justification of the methodology and risks

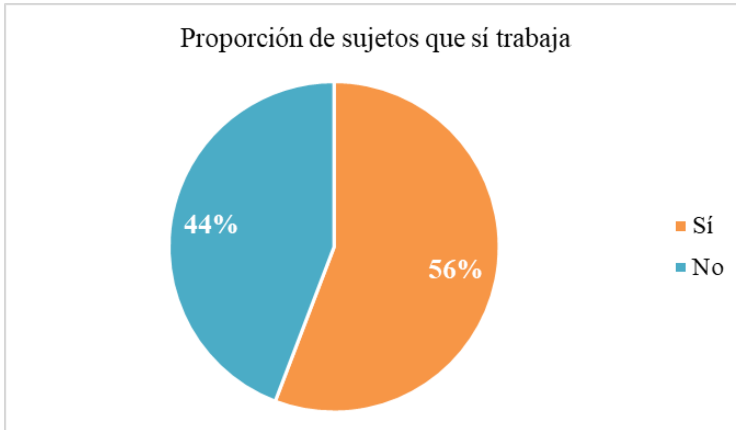
Now, stratification and convenience are used for sample selection. Convenience sampling is applied to the location for data collection instrument socialization (university center in the metropolitan area). In contrast to the data collection instrument used by PEN in 2018 (Waze database administered by MOPT), this study relies on electronic forms at the point of application, as it has access to the email database of 100% of the population. Mitigated risks included the low response probability and the probability of obtaining data from individuals outside the sample space (residents outside the metropolitan area). To address this, the obtained value from the sampling formula was doubled, as it did not represent a prohibitive cost. Finally, open-ended questions were not used since the relationship between subjects' routine movement patterns and the production of greenhouse gases derived from transportation does not depend on subjective criteria.

## Results

As a result of applying the instrument, a total of 841 valid responses were obtained, surpassing the double of what was recommended by the statistical formula. The survey response rate was 14.7%, and the proportion of responses useful for analysis was 13.5%. Figure 1 illustrates how to calculate the sample size using an online tool.

In Figure 3, it is observed that among the total number of eligible subjects for the study, the proportion of those who work and those who don't work is 56% for those who work and 44% for those who do not.

**Figure 3. Proportion of Working Subjects**




Source: Author's own work, 2023

In Table 1, the proportions for the place of residence of the survey respondents are listed. It was found that 96% of them reside in the provinces within the Greater Metropolitan Area (GAM).

**Table 1. Residence Location of Survey Respondents**

| Where do you currently reside? | Proportion |
|---|---:|
| San José | 57,9% |
| Heredia | 18,3% |
| Alajuela | 11,2% |
| Cartago | 8,8% |
| Puntarenas | 2,7% |
| Guanacaste | 0,6% |
| Limón | 0,6% |
| Total | 100,0% |

Source: Author's own work, 2023

The analysis of the results demonstrates a strong methodological approach in data collection. A total of 841 valid responses were obtained, significantly exceeding the recommended sample size, and validating the robustness of the research. The response rate of 14.7% reflects a high level of participation and cooperation from the studied population, enhancing the validity of the findings.

Moreover, Figure 1, illustrating the calculation of the sample size using an online tool, supports transparency and accuracy in the sample selection process, which is essential in scientific research to ensure population representativeness. While, Figure 2 highlights a significant distinction in the population based on their employment status, with 56% of respondents being employed and 44% not employed. This information is crucial for understanding mobility patterns, as employment tends to be a determining factor in people's mobility.

On the one hand, Table 1 provides a detailed description of the residential locations of the respondents, which is essential for understanding the geographical distribution of the study population. Surprisingly, 96% of the respondents reside in the Greater Metropolitan Area (GAM), suggesting that the majority of the surveyed population is located in densely populated urban areas. This data has significant implications for analyzing mobility dynamics and their impact on carbon footprint in urban settings.

In conclusion, the results demonstrate that the study was conducted with scientific rigor, achieving strong population participation and providing essential data to understand mobility and carbon footprint in an urban context.

Moreover, in Table 2, it is observed that out of the target population, 74.9% qualify for determining the distances traveled per day. The "Other" category corresponds to individuals who reside outside the Greater Metropolitan Area (Casco Metropolitano), even if they are registered as subjects belonging to the provinces of the GAM.

**Table 2. Population within the geographical boundaries**

| **Cantón** | **Proporción** |
|---|---:|
| San José | 18,7% |
| Heredia | 6,9% |
| Desamparados | 5,0% |
| Escazú | 4,4% |
| Curridabat | 4,0% |
| Santa Ana | 3,8% |
| Tibás | 3,4% |

| | |
|---|---|
| Montes de Oca | 3,4% |
| Santo Domingo | 3,4% |
| Goicoechea | 3,1% |
| Moravia | 2,9% |
| La Unión | 2,7% |
| Alajuelita | 2,5% |
| Vásquez de Coronado | 2,5% |
| San Rafael | 1,7% |
| San Pablo | 1,7% |
| Mora | 1,5% |
| Aserrí | 1,0% |
| Flores | 1,0% |
| Barva | 0,8% |
| Belén | 0,8% |
| Otro | 25,1% |
| Total | 100,0% |

Source: Author's own work, 2023.

Furthermore, Table 3 summarizes the calculation of kilometers traveled per week within the studied routes, which is close to 115,000. The day with the least movement between points of interest is Tuesday.

**Table 3. Population within the geographical boundaries**

| Day | Ruta 1 | Ruta 2 | Población R1 | Población R2 | Total kms |
|---|---|---|---|---|---|
| Monday | 84,6% | 15,4% | 712 | 129 | 24.311 |
| Tuesday | 68,4% | 31,6% | 575 | 266 | 19.643 |
| Wednesday | 85,0% | 15,0% | 715 | 126 | 24.422 |
| Thursday | 83,3% | 16,7% | 701 | 140 | 23.941 |
| Friday | 85,0% | 15,0% | 715 | 126 | 24.422 |
| Total | | | | | 116.740 |

Source: Author's own work, 2023.

Table 4 displays the workplaces that coincided with the mobility detected by the National Emergency Commission (PEN) in 2018 (Barrantes, 2018). Three of the destinations were not observed during the data collection phase and are shown in Table 4 as zeros (0.0%).

**Table 4. Workplaces of the studied population (destinations)**

| Workplace (destination) | Proportion |
|---|---|
| Zonas industriales Heredia (Metro, Lagunilla o similares) | 47,4% |
| Zonas industriales Alajuela (Coyol, ZETA o similares) | 34,0% |
| Zonas industriales Cartago (La Lima o similares) | 6,3% |
| Lindora | 4,6% |
| Escazú | 3,5% |
| San José Norte (Tibás/Moravia y alrededores) | 2,7% |
| San José Este (Curridabat y alrededores) | 1,2% |
| Belén | 0,3% |
| Tres Ríos | 0,0% |
| San José Sur (Desamparados y alrededores) | 0,0% |
| San José Oeste (Pavas y alrededores) | 0,0% |
| Total | 100,0% |

Source: Author's own work, 2023.

Table 5 illustrates that the most common mode of transportation is a personal vehicle (including two-wheeled vehicles with combustion engines). The second most important is the bus, and the third is taxi/Uber services.

**Table 5. Means of transportation used from residence to the workplace**

| Means of transportation from residency to workplace | Proportion |
|---|---|
| Private vehicle (including motorcycles) | 48,0% |
| Bus (including company-provided transportation) | 28,7% |
| Taxi/Uber (solo or shared) | 21,9% |
| Travels in a car with others (they pick you up/carpooling) | 1,4% |
| Total | 100,0% |

Source: Author's own work, 2023.

Table 6 shows that the mode of transportation from the workplace to the educational center maintains the same structure as from residence to work. Moreover, the bus has seen an increase of approximately 5 percentage points at the expense of taxi or Uber usage.

**Table 6. Means of transportation used from work to the educational center**

| Means of transportation used from work to the educational center | Proportion |
|---|---|
| Private vehicle (including motorcycles) | 48,0% |
| Bus (including company-provided transportation) | 36,3% |
| Taxi/Uber (solo or shared) | 12,7% |
| Travels in a car with others (they pick you up/carpooling) | 3,0% |
| Total | 100,0% |

Source: Author's own work, 2023.

Now, the analysis of the results is based on a robust methodology of data collection, which has yielded a set of key findings. Below is a general analysis summarizing the results and their implications.

Firstly, a total of 841 valid responses were obtained, significantly exceeding the recommended sample size. This validates the study's strength and the strong participation of the studied population, with a response rate of 14.7%. Regarding the studied population, it is observed that 56% of the respondents are employed, while 44% are not. This distinction is essential for understanding mobility patterns, as employment is often a determining factor in people's travel.

Furthermore, the residence locations of the respondents reveal that 96% of them reside in the Greater Metropolitan Area (GAM). This suggests that most of the population is in densely populated urban areas, which has significant implications for analyzing mobility and its impact on the carbon footprint in urban environments.

Regarding mobility, data was collected on the means of transportation used from residence to the workplace and from the workplace to the educational center. The results show that personal vehicles, including motorcycles, are the most common means of transportation, followed by buses and taxi/Uber services. The locations of the workplaces coincide with the mobility observed in a previous study conducted by the National Emergency Commission (PEN). This data is essential for understanding mobility patterns and the most frequently traveled routes.

In general, these results provide a detailed insight into the mobility patterns of the studied population and their impact on the carbon footprint in an urban setting. This data is crucial for understanding mobility dynamics, and can inform future research and policies related to carbon emission reduction in urban areas.

Moreover, in Table 7, it is observed that the most popular means of transportation from the educational center to the place of residence remains the personal vehicle. The bus, for example, has seen an increase of approximately 8% points compared to the "workplace to educational center" route. On the other hand, the use of taxis or Uber decreases to accommodate this shift.

**Table 7. Means of transportation used from the educational center to the residence**

| Means of transportation from the educational center to the residence | Proportion |
|---|---:|
| Private vehicle (including motorcycles) | 48,0% |
| Bus (including company-provided transportation) | 44,6% |
| Taxi/Uber (solo or shared) | 5,4% |
| Travels in a car with others (they pick you up/carpooling) | 2,0% |
| Total | 100,0% |

Source: Author's own work, 2023.

Table 8 shows how the surveyed subjects predominantly commute on all five days of the week. This refers to the number of days that the population uses for commuting weekly, either to the workplace or the educational center.

**Table 8. Weekly Commuting (Frequency)**

| Weekly travels | Proportion |
|---|---|
| 1 | 3,6% |
| 2 | 2,9% |
| 3 | 7,6% |
| 4 | 0,0% |
| 5 | 41,7% |
| Total | 55,8% |

Source: Author's own work, 2023.

Table 9 demonstrates that the number of days the population uses for commuting weekly, whether from the workplace to the educational center or from residence to the educational center. This situation occurs all five days of the week, with a greater concentration in the segments of 2 to 4 times per week.

**Table 9. Attendance at the Educational Center (Frequency)**

| Days per week | Proportion |
|---|---|
| 1 | 7,1% |
| 2 | 33,0% |
| 3 | 25,7% |
| 4 | 21,8% |
| 5 | 12,5% |
| Total | 100,0% |

Source: Author's own work, 2023.

Table 10 summarizes the results for the time spent commuting on “route 1” (residence-work-educational center). It shows that the study subjects use an average of 2.8 hours per day, with a standard deviation of 1.5 hours.

**Table 10. Hours Spent Commuting (Route 1)**

| Time spent on transportation | Hours |
|---|---|
| Average | 2,8 |
| Standard deviation | 1,5 |
| Variance | 2,2 |

Source: Author’s own work, 2023.

Table 11 displays the time spent commuting on “route 2” (residence-educational center) and shows that the study subjects use an average of 1.5 hours per day, with a standard deviation of 0.7 hours.

**Table 11. Hours Spent Commuting (Route 2)**

| Time spent on transportation | Hours |
|---|---|
| Average | 1,5 |
| Standard deviation | 0,7 |

Source: Author’s own work, 2023.

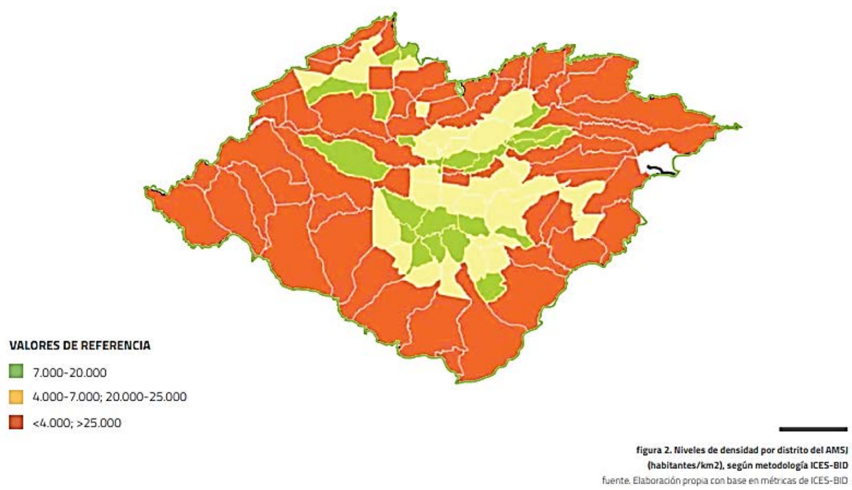
## Discussion

According to the Ministry of Environment and Energy of Costa Rica, in its “Fourth National Communication to the United Nations Framework Convention on Climate Change” from 2021, approximately 43% of greenhouse gas (GHG) emissions are attributed to the “Transport” sector. This data is based on an inventory conducted in 2017. In its 2018 report, the National Emergency Commission (PEN) (Chapter 6) noted that

> 90% of the High-Capacity Network does not meet the parameters of the National Transport Plan regarding the number of lanes. In the absence of changes, the percentage of routes with major traffic problems would increase from 48% in 2017 to 86% in 2025.

As shown in Figure 3, ACA & Gensler in their 2017 report "PIMUS. Comprehensive Plan for Sustainable Urban Mobility for the Metropolitan Area of San Jose, Costa Rica," the Greater Metropolitan Area is in a critical situation, given its density (calculated using ICES-BID metrics).

**Figure 4. Population Density in Inhabitants per Square Kilometer in the Greater Metropolitan Area**

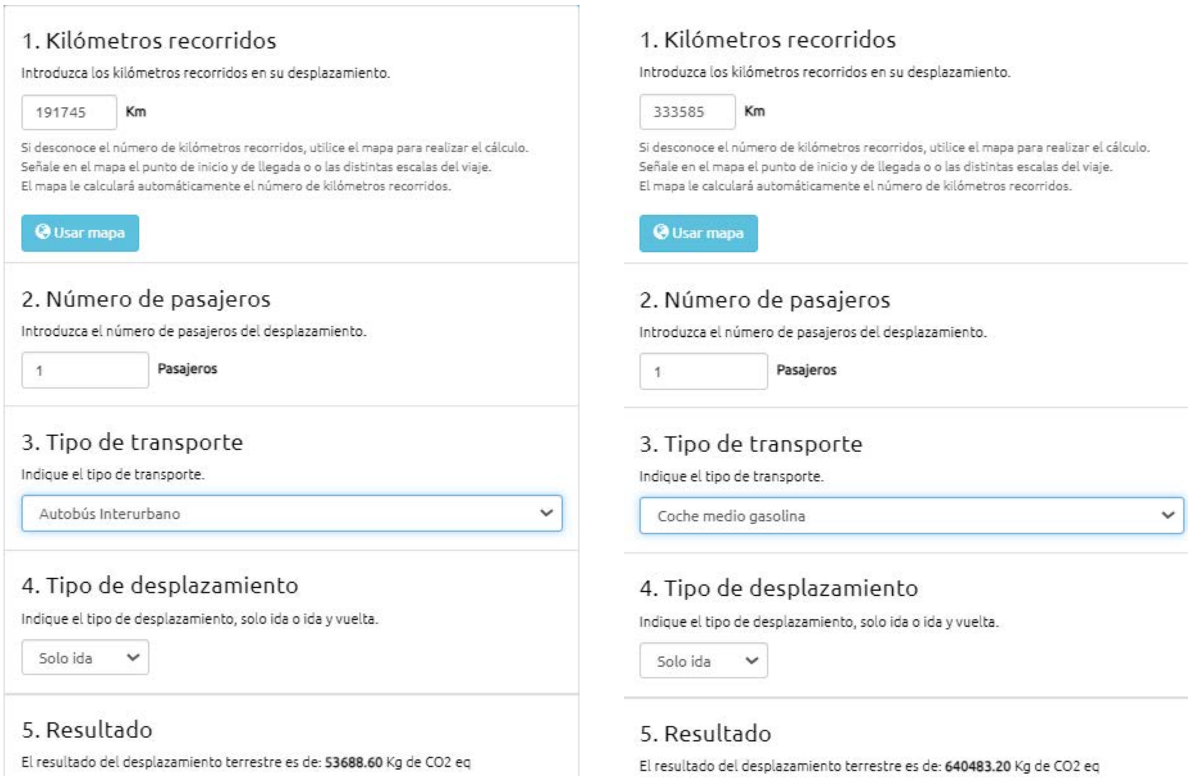



Source: ACA & Gensler. PIMUS. Comprehensive Plan for Sustainable Urban Mobility for the Metropolitan Area of San Jose, Costa Rica.

Furthermore, the findings published in the "2023 IMD Smart City Index" show that traffic congestion is not directly related to the size or population density of cities, but rather to the alignment of public policies (commerce, road planning, and regulatory plans). This is evident in cities like Zurich, Oslo, Singapore, Beijing, Seoul, and Hong Kong, known as "super champions." However, other cities perceived as "chaotic" have also made positive progress within the index, including Montreal, Denver, Lausanne, Bilbao, Bangalore, Brisbane, Busan, Sydney, Hong Kong, and Shanghai.

The result obtained for the carbon footprint (typified by fuel), using the online tool "Greenhouse Gas Emissions Calculators" from ceroco2.org (Figure 4), is 694,172 kg of CO2 (0.7 metric tons). The per capita carbon footprint per commute is 0.83 metric tons. Compared to the reference published by the World Bank Group (2020) of 1.36 metric tons, transportation contributes to 64% of the indicator in the Greater Metropolitan Area, in line with what was described by PEN in Chapter 6 of its 2018 report: "50% of workers work in a canton different from their place of residence. Outside the GAM, this figure drops to only 18%."

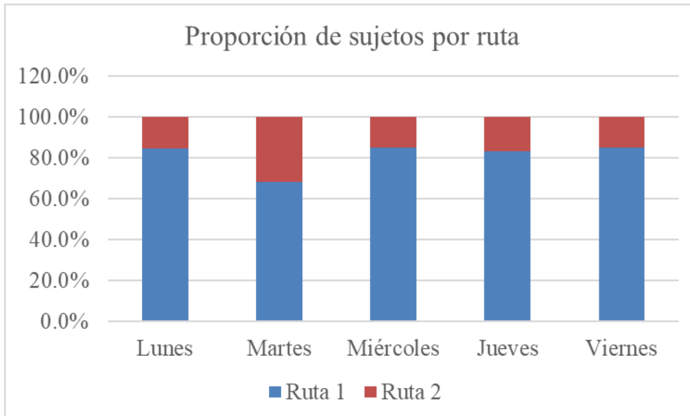
**Figure 5. Greenhouse Gas Emissions (Carbon Footprint) Calculation**




Source: ceroco2.org.

Figure 6 illustrates how the proportion of subjects traveling along Route 1 (residence-workplace-educational center) remains close to 85% during the week, except for Tuesday when the ratio shifts to 2:1 (68.4% / 31.4%). The study did not delve into the reasons for this behavior.

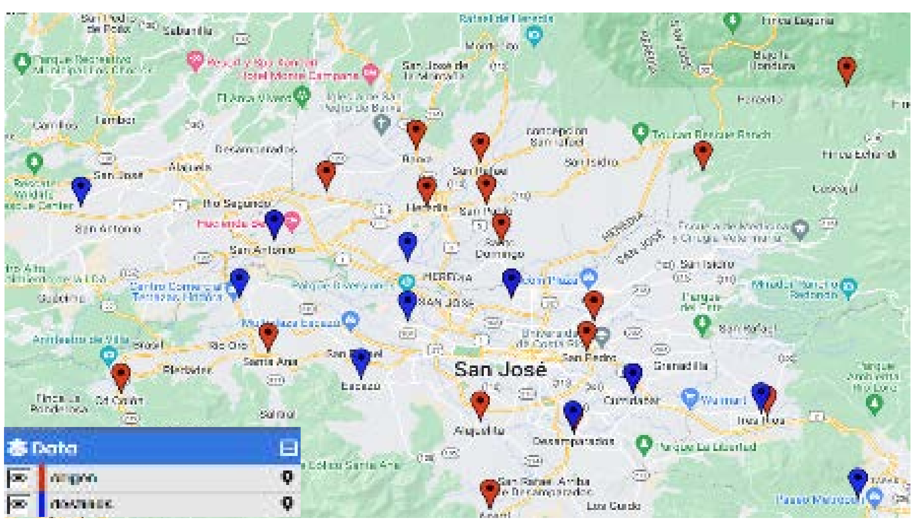
**Figure 6. Proportion of Subjects by Commuting Route**




Source: Author's own work, 2023.

Additionally, the concentration of the study population confirms the National Emergency Commission's (PEN) thesis in Chapter 6 of the 2018 Report, but from a different perspective (place of residence). The PEN detailed the origins of commuting routes based on peak hours and WAZE reports, which helped create two datasets. The first dataset corresponds to the morning rush hour, and the second to the evening rush hour (17:00 p.m. to 19:00 p.m.). The PEN's methodology is more precise as it collects georeferenced data from any application user over a span of several months. In this case, the study relies on what the subject claims as their response within the data collection instrument (Figure 7).

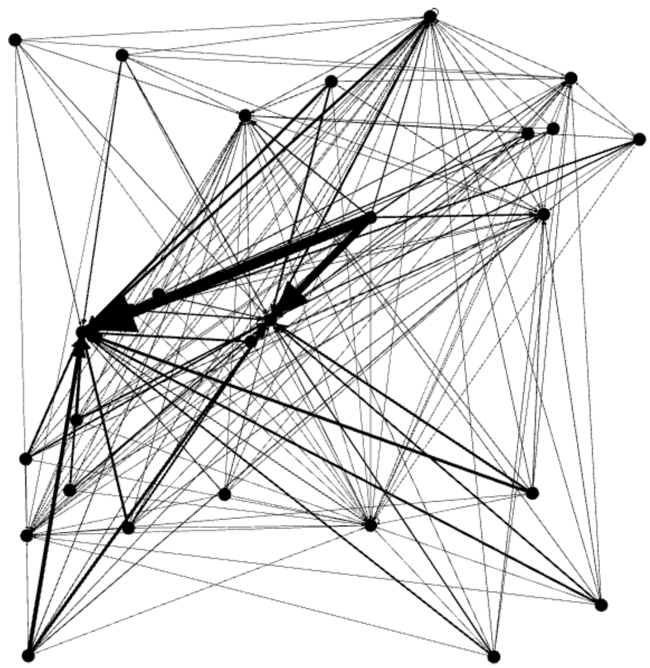
**Figure 7. Location of Origins/Destinations for Commuting Routes**




Source: Author's own work using maps.co/gis/.

Using graphs and node analysis (Figure 8), the routes with the highest concentration of trips were obtained. These are illustrated by the following thick lines and arrows.

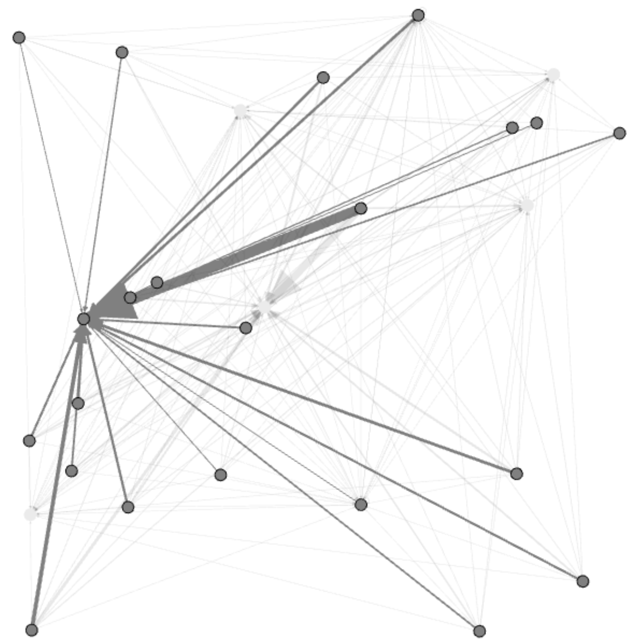
**Figure 8. Node Analysis of Commuting from Residence to Workplace**



Source: Author's own work using Gephi, 2023.

On one hand, Figure 9 displays the most heavily trafficked nodes, determined using filters within the Gephi tool to obtain these specific results.

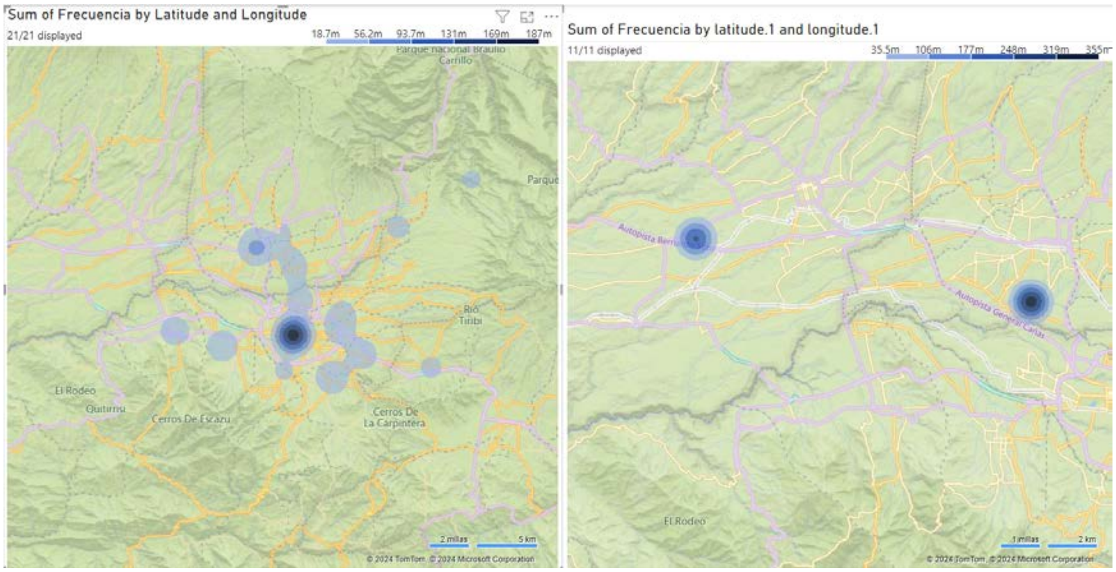
**Figure 9. Most Trafficked Nodes in Commuting from Residence to Workplace**



Source: Author's own work using Gephi, 2023.

Figure 10 summarizes the traffic within the segment. To contextualize the information, a dimensionless scale was used (transforming the weight of the segment on the route into an integer number), so that the nodes reflect their respective traffic in relation to the others.

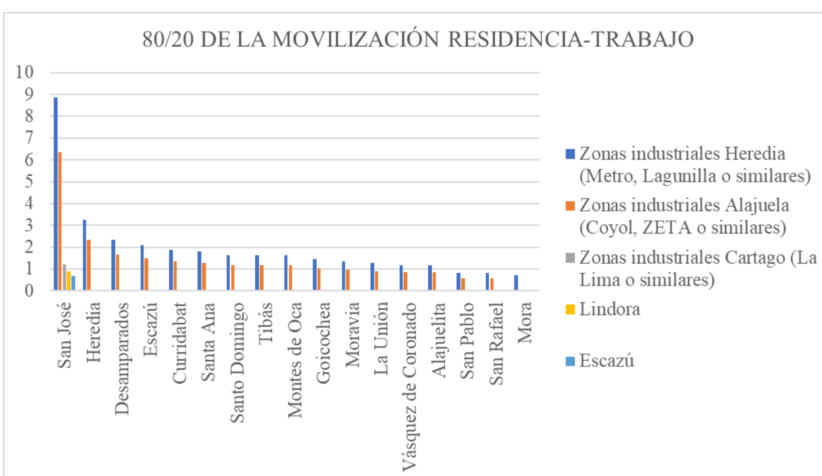
**Figure 10. Heatmap for the starting/destination Nodes in Commuting from Residence to Study Center to Workplace**




Source: Author's own work, 2023.

As can be seen in Figure 11, commuters from San Jose travel to workplaces outside its borders, such as Heredia, Alajuela, and Cartago. To a lesser extent, residents of the central canton commute to centers located in the west, such as Lindora and Escazú.

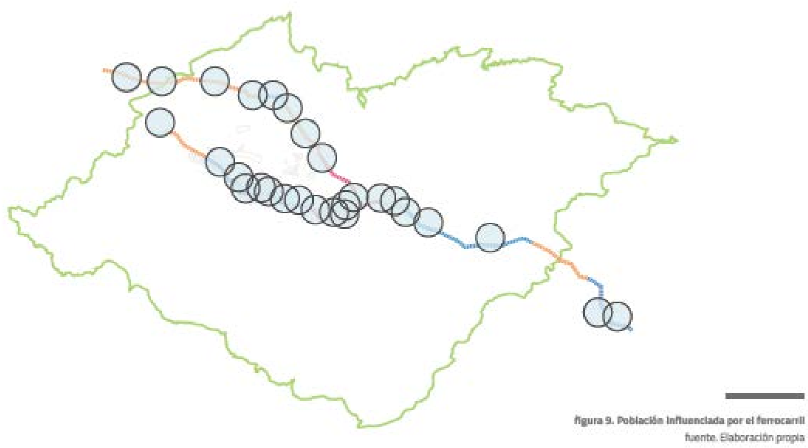
**Figure 11. Most Trafficked Nodes in Commuting from Residence to Workplace**




Source: Author's own work, 2023.

Finally, this finding aligns with what AC&A and Gensler (2017) proposed in their executive summary of PIMUS. The Greater Metropolitan Area mobilizes people in the East-Northwest direction, in line with the nodes revealed by the instrument (Figure 12).

**Figure 12. Most Trafficked Nodes in Commuting from Residence to Workplace**




Source: AC&A, Gensler. Executive Summary PIMUS 2017.

These nodes reflect the highest demand for movement within the study, and, as a result, they significantly contribute to greenhouse gas emissions (GEI) production. Lui et al. (2023) conclude that the relationship between public policies (commerce, urbanization plans, transportation, health, and information) in a proper mix can positively influence the reduction of GEI by allocating budgets and operational resources to implement different modalities in the road network, as seen in the case of China's use of trains.

Confirming what AC&A and Gensler (2017) proposed in the "Comprehensive Plan for Sustainable Urban Mobility for the Metropolitan Area of San Jose, Costa Rica," the rights of way for mass mobility, such as trains, provide an alternative to the reduced productivity resulting from long travel times between nodes. In this case, the plan suggests the inclusion of electric trains as a mode of transportation, which, in turn, would contribute to the reduction in GEI production.

Regarding the fulfillment of the objectives of the Carbon Neutrality Country Program 2.0 (Rona, 2019) by 2050, the per capita GEI should register an indicator of 1.19 metric tons. In 2020, the World Bank Group reported 1.36 for the country. However, the trend within the Greater Metropolitan Area is on the rise, so controlling this effect relies on rural areas (with fewer motorized populations), carbon capture (tree planting or increasing green areas), and finally, reorganizing the road network within the metropolis.

This study also provides a basis for expanding the scope and using numerical methods for the precise estimation of this indicator.

Pérez et al. (2015) consider that cities continue to grow, and the challenges associated with their planning must be deeply thought out to align demographic growth, economic sustainability, and social progress. Therefore, proposed solutions must maintain a holistic approach; this is the concept of a “Smart City”.

This study offers a data collection model for determining mobility patterns in the most active sector of the economy, not necessarily the one that offers the highest economic content. Nevertheless, it can be refined and expanded by using the network of higher education institutions in the country, with institutional cooperation as a platform for socialization. The findings are consistent with what is described in the literature, despite using different data capture methods and a convenience sample within a much more limited time window. Therefore, it can be improved (in its content) and used in future studies or replications.

## Conclusion

The study conducted on the reduction of carbon footprint due to traffic congestion in the Greater Metropolitan Area (Casco Metropolitano) reveals that the mobility patterns of one of the most active segments of society (university students aged 18-24, residents of the GAM) provide relevant information related to the issues already discussed in the literature. This confirms that the instrument is reliable and allows for future replications.

In line with the results obtained by Barrantes (2018), the concentration of workplaces in free trade zones and similar conglomerates can work in favor of implementing mass transportation methods with low impact on greenhouse gas emissions (GEI) production. This is exemplified in the recommendation made by AC&A and Gensler (2017), who suggest the construction of railway routes to serve the demand from Cartago to the two most representative nodes: Heredia and Alajuela. The technology suitable for achieving the goal of reducing the carbon footprint is powered by electricity.

The findings regarding the level of compliance to achieve the Carbon Neutrality objective by 2050 show that the reported per capita value is highly influenced by areas outside the urban center. In the Greater Metropolitan Area, the GEI values obtained indicate that the transportation sector contributes a 61% of the country’s indicator (0.83 out of 1.36 metric tons). Therefore, to reverse the growing trend in the carbon footprint, it is possible to consider implementing measures used in other countries (utilizing technology) to reorganize the road network, urban planning, accessibility, and mass transportation. The growth of the vehicle fleet increased from 750,000 to nearly 900,000 units between 2015 and 2017, a

20% increase, according to data from the 2018 PEN Report. This behavior is contrary to the goal of reducing the carbon footprint. Implementing Smart City practices can help achieve the goal.

Improvements in the road network to promote traffic flow are linked to reforms in policies and societal behavior. Staggering working hours in public institutions, promoting digital access to information through websites, reducing administrative procedures, and increasing facilities for transactions (requests, payments, inquiries), as well as improving urban safety so that individuals can move with fewer concerns, are some of the strategies used in Smart Cities, according to Carballo et al. (2019).

Finally, the conversion of bus stops into stations is another strategy used in cities in countries such as Vietnam (Hương et al., 2023). The perceived benefits include increased commercial activity from pedestrian traffic in the city center, reduced noise levels, and lower pollution. The decongestion of roads due to a reduction in buses positively affects vehicle traffic on the city's cross streets. Technical solutions, such as those offered by Yi et al. (2018), with the application of the ACO algorithm to traffic lights, remain to be explored further.

## Recommendations

The study conducted demonstrates that, as a replication of other publications cited in the literature, less technologically advanced and less restrictive instruments can be used. The PEN sought the CENAT and MOPT for high-level data processing and large-scale data storage, as well as access to the WAZE database. This is a step towards the democratization of information, as in this case, the request to MOPT to use the WAZE database remains unanswered by the institution.

If broader reach is intended and using a model of institutional collaboration, it is recommended to apply the instrument within the higher education system throughout the country. In this way, the greenhouse gas inventory, data updates on mobility, and the inclusion of other relevant information can help improve accuracy regarding the national carbon footprint. This information contributes to the efforts of the Ministry of Environment and Energy, as outlined in the Carbon Neutrality Country Program 2.0.

Regarding city reorganization, there is not much that can be done architecturally. The strategy of expropriations for road expansion is unviable. Instead, a technical study of traffic flow using technology (cameras and counters) and qualified labor (university students working on theses or during internships) can be employed. The application of mathematical algorithms, in conjunction with computational power, can manage scenarios that consider time bands (for correlating hours and congestion areas), days, events (road maintenance, accidents), and other possible variables; for example, Ant Colony Optimization has proven to be a robust analytical technique for such cases. Replicating or modifying what was achieved by Yi et al. (2018) is a good starting point.

Society, in general, must be informed of the progress in decarbonization, as few individuals outside of active circles are aware of the initiatives, indicators, efforts, and commitments of the country for 2050, as mitigating the carbon footprint in Costa Rica is closely linked to the green area (land planted, especially with timber species). Reducing the vehicle fleet does not seem to be a viable alternative, given the economic benefits for the country in terms of tax revenue, and curbing the growth of the vehicle fleet implies a politically sensitive position, as it is a growing and powerful industry. Therefore, focusing on reforestation and caring for areas that capture CO2 is the most recommended course of action currently.

Furthermore, the Smart City approach (with a broader spectrum of variables to complete the perspective) can be the next step to consider. The carbon footprint in the metropolitan area continues to be measured with the same criteria as 30 years ago. The use of standards such as ISO/IEC 30182:2017 – Smart City Concept Model for the design of smart cities can provide more comprehensive frameworks when seeking to reduce the carbon footprint, particularly addressing traffic congestion.

## References

AC&A., Gensler. (2017). *PIMUS. Plan integral de movilidad urbana sostenible para el área metropolitana de San José, Costa Rica*. Ministerio de Energía y Ambiente. https://cambioclimatico.go.cr/wp-content/uploads/2018/09/PIMUS_INFORME-EJECUTIVO.pdf

Alvarado, L. (2021). *Proyecciones de cambio climático regionalizadas para Costa Rica (Escenarios RCP-2.6 y RCP-8.5)*. Programa de cambio climático.

http://cglobal.imn.ac.cr/index.php/publications/proyecciones-de-cambio-climatico-regionalizadas-para-costa-rica-escenarios-rcp-2-6-y- rcp-8-5/

Ashhad, T., Cabrera, F. y Roa, O. (2020). Análisis del congestionamiento vehicular para el mejoramiento de vía principal en Guayaquil-Ecuador. *Revista Gaceta Técnica*. *21*(2), 4-23. https://doi.org/10.13140/RG.2.2.21905.04960

Grupo Banco Mundial. (2020). *Emisiones de CO2 (toneladas métricas per cápita)*. Centro de Análisis de Información sobre Dióxido de Carbono, División de Ciencias Ambientales del Laboratorio Nacional de Oak Ridge. https://datos.bancomundial.org/indicator/EN.ATM.CO2E.PC?end=2020&start=1990&view=map

Barrantes, R. (2018). *Diagnóstico sobre el estado de la Infraestructura vial en Costa Rica movilidad de bienes y servicios*. Estado de la Nación. https://hdl.handle.net/20.500.12337/2957

Carballo, L., Villagra, A. y Errecalde, M. (2019). Movilidad inteligente: reducción de emisión de gases. *Informes Científicos Técnicos - UNPA*, *11*(2), 53–69. https://doi.org/10.22305/ict-unpa.v11i2.786

Fueyo, M. (2021) *Estudio de la huella de carbono de la Universidad de Cantabria*. [Tesis de grado en Ingeniería Química, Universidad de Cantabria]. http://hdl.handle.net/10902/22423

Gobierno de Costa Rica, Ministerio de Ambiente y Energía. (2021). *Costa Rica 2021: Cuarta Comunicación Nacional a la Convención Marco de Naciones Unidas sobre el Cambio Climático*. Programa de las Naciones Unidas para el Desarrollo. https://www.undp.org/es/costa-rica/publications/cuarta-comunicaci%C3%B3n-nacional-convenci%C3%B3n-marco-de-las-naciones-unidas-sobre

Hương, T., Lam, T. & Vuong, H. (2023). *Smart Cities in the World, Value Creation, and Suggestion for Vietnam*.

International Institute for Management Development. (2023). *IMD Smart City Index Report 2023*. https://www.imd.org/news/competitiveness/asian-and-european-citizens-see-their-cities-as-the-smartest-finds-2023-imd-smart-city- index/

Kitpo, N., Kugai, Y., Inoue., M, Yokemura, T., Satomura, S. (2019, 11-13 de enero). *Internet of Things for Greenhouse Monitoring System Using Deep Learning and Bot Notification Services*. [Sesión de conferencia] 1- 4. IEEE International Conference on Consumer Electronics (ICCE), Las Vegas, Estados Unidos. https://doi.org/10.1109/ICCE.2019.8661999

Lanvin, B. (2023). *Asian and European citizens see their cities as the 'smartest', finds 2023 IMD Smart City Index*. IMD. https://www.imd.org/news/competitiveness/asian-and-european-citizens-see-their-cities-as-the-smartest-finds-2023-imd-smart-city- index/

Liu, K., Meng, C., Tan, J., Zhang, G. (2023). Do smart cities promote a green economy? Evidence from a quasi-experiment of 253 cities in China, *Environmental Impact Assessment Review*, *99*. https://doi.org/10.1016/j.eiar.2022.107009. (https://www.sciencedirect.com/science/article/pii/S019592552200275X

Machado, D., Qu, Y., Cervantes, M. (2019). Innovation policies for sustainable development: Low-carbon energy and smart-city initiatives. *OECD Science, Technology and Industry Policy Papers,* (80). https://doi.org/10.1787/23074957

Naciones Unidas. (12 de diciembre del 2015). *Acuerdo de París de la Convención Marco de las Naciones Unidas sobre el Cambio Climático (UNFCCC)*. https://www.refworld.org.es/docid/602021b64.html

NOAA National Centers for Environmental Information (2023). *Monthly Global Climate Report for Annual 2022*. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202213/supplemental/page-6.

Pérez, F., Velásquez, G., Fernández, G., Dorao, V. (2015) Movilidad inteligente. *Economía industrial*. (395): 111-122. https://www.ospi.es/export/sites/ospi/documents/documentos/Economia-Industrial.pdf

Pishue, B. (2023). *2022 INRIX global traffic scorecard. Annual Report*. Kirkland,WA, USA.https://lesvoitures.fr/wp- content/uploads/2023/01/2022_INRIX_Traffic_Scorecard_Report.pdf

Poudenx, P. (2008). The effect of transportation policies on energy consumption and greenhouse gas emission from urban passenger transportation, *Transportation Research Part A: Policy and Practice, 42*(6): 901-909. https://doi.org/10.1016/j.tra.2008.01.013.(https://www.sciencedirect.com/science/article/pii/S0965856408000402

Presidencia de la República. *Ministerio de Comunicación. (2020). Costa Rica registra una reducción del 26% en emisiones de dióxido de carbono por la pandemia*. https://www.presidencia.go.cr/comunicados/2020/08/costa-rica- registra-una-reduccion-del-26-en-emisiones-de-dioxido-de-carbono-por-la-pandemia/#:~:text=Minutos%20de%20lectura,Costa%20Rica%20registra%20una%20reducci%C3%B3n%20del%2026%25%20en%20emisiones%20de,de%20carbono%20por%20la%20pandemia&text=Informe%20del%20IMN%20midi%C3%B3%20el,con%20ese%20periodo%20en%202019.

Rona, N. (2019). Costa Rica: Programa País de Carbono Neutralidad 2.0 – Categoría Organizacional. Estudio de Caso. https://ledslac.org/wp-content/uploads/2020/05/EdC-Carbono-Neutralidad-Costa-Rica-ene20_mod.pdf

Schirn, A. (2022). *ISO/IEC 30182:2017 –Smart City Concept Model*. American National Standards Institute. https://blog.ansi.org/iso-iec-30182-2017-smart-city-concept-model/#gref.

Suresh, B., Moondra, N., Tandel, B. (2019). Assessment of carbon footprint: a case study of SVNIT campus. *Recent trends in civil engineering, 77*, 1030-1036. http://dx.doi.org/10.1007/978-981-15-5195-6_75

Sharifi, A., Allam, Z., Feizizadeh, B., Ghamari, H. (2021). Three Decades of Research on Smart Cities: Mapping Knowledge Structure and Trends. *Sustainability,* (13): 7140. https://doi.org/10.3390/su13137140

Syed, A., Sierra-Sosa, D., Kumar, A., Elmaghraby, A. (2021). IoT in Smart Cities: A Survey of Technologies, Practices and Challenges. *Smart Cities* (4): 429–475. https://doi.org/10.3390/smartcities4020024

Taha, H. Investigación de operaciones. (2017). Pearson Educación, México.

Wade, M., Pfaeffli, M. (mayo del 2016). *What is a Smart City anyways?* International Institute for Management Development. https://www.imd.org/research- knowledge/technology-management/articles/what-is-a-smart-city-anyways/

Wang, F. (2023). Does the construction of smart cities make cities green? Evidence from a quasi-natural experiment in China. *Cities*, *Vol 140*(3). https://doi.org/10.1016/j.cities.2023.104436.)

Wang, L., Chen, R., Sun, W., Yang, X., Li, X. (2019). Impact of High-Density Urban Built Environment on Chronic Obstructive Pulmonary Disease: A Case Study of Jing'an District, Shanghai. I*nt J Environ Res Public Health*. *Vol 17*(1): 252. doi: 10.3390/ijerph17010252.

Yi, Z., Fazhi, H., Neng, H., Yimin, Q. (2018). Parallel ant colony optimization on multi-core SIMD CPUs. Future Generation Computer Systems, Vol 79(2): 473-487. https://doi.org/10.1016/j.future.2017.09.073. https://www.sciencedirect.com/science/article/pii/S0167739X16304289