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Design of an Electric Cargo Tricycle (E-Trike Cargo) for the Collection of Recyclable Solid Waste in the City Of Popayán (Phase 1)

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Abstract: This article presents the design of an electric cargo tricycle (E-trike cargo) aimed at improving the management of recyclable solid waste in the city of Popayán, Colombia. The study is divided into three stages: analysis of road infrastructure, implementation of last-mile logistics, and detailed design of the electric tricycle. The first stage analyzes the main road network in downtown Popayán, identifying the most important streets, tourist points, and pedestrian traffic distribution. Traffic patterns are studied, including variability during different times of the day, identifying Calle 4 as a critical congestion point. The conditions of the pavement, signage, road safety, pedestrian and cyclist infrastructure, intersections and crossings, parking, and public transportation are also evaluated. The second stage explores the implementation of last-mile logistics for the collection of recyclable solid waste in downtown Popayán. This includes the use of technologies such as route optimization algorithms, IoT sensors to monitor containers and vehicles, fleet management systems for real-time tracking and control, and mobile applications for drivers and users. The third stage presents the general plans of the E-trike cargo, detailing its components, including the chassis and structure, propulsion system, energy system, sensor systems, comfort and safety features, tires, monitoring and communication systems, and cargo components

The analysis of the results highlights the feasibility, environmental impact, and improvements in working conditions that the E-trike cargo can generate. However, it also emphasizes the need for investments, training, and appropriate regulations for its successful implementation. The project concludes that the E-trike cargo is a viable and beneficial solution, but a coordinated effort, supported by adequate investments and institutional support, is required to ensure its sustainability and long-term success. Collaboration between local authorities, the community, and the private sector will be essential to overcome challenges and maximize the benefits of this innovative waste collection solution.

Keywords: CAD design, E-trike, recyclable solid waste, last-mile logistics

I. INTRODUCTION

In a world where sustainability and efficiency in waste management are imperative, the need arises to innovate in cargo transport solutions that facilitate the collection of recyclable materials in urban environments. With this purpose in mind, the project of designing an electric cargo tricycle for the collection of recyclable solid waste in the city of Popayán is presented as a comprehensive and sustainable response to the current challenges faced by waste management in urban areas. This includes the creation of an act for the evaluation of projects that benefit from the incentive resource for the use and treatment of solid waste (Alcaldia de Popayán, 2022). Popayán, known for its rich history and cultural heritage, faces significant challenges regarding the efficient collection of recyclable waste. As environmental awareness grows in the city, it is essential to have a waste collection system that is not only effective but also environmentally friendly and adaptable to the specific needs of the community.

This project aims to design an electric cargo tricycle capable of safely and efficiently transporting a variety of recyclable materials, from paper and cardboard to plastic and glass, optimizing collection processes and thus contributing to waste reduction in the city. In addition to its practical functionality, this tricycle is intended to be a sustainable option, with zero carbon emissions and minimal impact on the urban environment.

Through the combination of advanced technology, innovative design, and a community-centered approach, this project aspires to offer a comprehensive solution to improve waste management in the city of Popayán, while promoting more sustainable practices and contributing to the environmental well-being of the region. In the current context of environmental concern and sustainability, efficient solid waste management has become a priority for many cities and communities worldwide.

In this sense, the adoption of electric vehicles for the collection of recyclable solid waste represents a significant step towards reducing carbon footprint and promoting more sustainable waste management practices. Solid waste management presents significant challenges in terms of environmental impact, operational efficiency, and associated costs. Traditionally, waste collection vehicles have been powered by internal combustion engines, resulting in greenhouse gas emissions and noise, as well as higher operating and maintenance costs. Additionally, the selective collection of recyclable solid waste, such as cardboard and plastic, requires efficient logistics and appropriate transportation systems to ensure proper processing and recycling. In this regard, the implementation of electric cargo vehicles offers a promising solution to address these challenges comprehensively.
"A cargo electric vehicle specifically designed for the collection of recyclable solid waste offers a series of key advantages:"

1) Zero Emissions: Being powered by an electric motor, the vehicle emits no exhaust gases and produces no noise, significantly reducing air pollution and noise in urban areas.
2) Energy Efficiency: Electric vehicles are inherently more efficient than their internal combustion counterparts, resulting in lower operating costs and greater range per charge.
3) Low Maintenance: Electric motors have fewer moving parts and require less maintenance than internal combustion engines, resulting in lower maintenance costs over the vehicle's lifespan.
4) Quiet: The silent operation of electric vehicles makes them ideal for use in residential and urban areas, where noise can be a concern.
5) Adaptability: Electric cargo vehicles can be designed to meet the specific needs of solid waste collection, with features such as adjustable cargo compartments, container lifting systems, and variable load capacity.
6) Technological Integration: Electric vehicles can integrate advanced technologies such as telemetry systems and fleet management to optimize operational efficiency and route scheduling.

The adoption of electric cargo vehicles for the collection of recyclable solid waste represents a significant step towards building more sustainable and environmentally-friendly cities. These vehicles not only offer significant environmental benefits by reducing greenhouse gas emissions and noise pollution, but they can also improve operational efficiency and reduce long-term costs for local authorities and waste management companies.
Ultimately, investing in infrastructure and technology for the implementation of electric cargo vehicles in solid waste collection not only benefits the environment but also promotes innovation and the development of sustainable solutions for current urban challenges.

II. METHODOLOGY

The design of the electric cargo tricycle (E-trike cargo) for the collection of recyclable solid waste in Popayán, phase 1, will follow a methodical approach that encompasses several key stages.
It will begin with a comprehensive analysis of the road infrastructure in the selected areas for the initial tests, including the evaluation of street conditions, bike lanes, slopes, and other relevant factors that may influence the design and operation of the E-trike cargo.
Subsequently, interviews and surveys will be conducted with recyclable solid waste collectors in Popayán to thoroughly understand their current logistical processes. The distribution of collection routes, working hours, critical points, and specific needs of the collectors will be investigated.
Gathering data on the technical characteristics necessary for the design of the E-trike cargo will be fundamental. This will include parameters such as load capacity, battery range, maximum speed, terrain resistance, and maneuverability. These data will be used as a basis to inform the vehicle design.
Based on this data and the identified needs of the collectors, initial design concepts for the E-trike cargo will be developed. Different configurations and features will be explored with the aim of optimizing the efficiency and comfort of the vehicle.
Finally, 3D modeling tools will be used to create virtual prototypes of the conceptual design of the E-trike cargo, allowing for detailed visualization and evaluation before advancing to the physical prototyping stage.

A. STAGE I

Popayán, the capital of the Cauca department in Colombia, is a historically and culturally significant city, with road infrastructure that reflects its importance as an urban and economic center in the region.

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The objective is to provide an overview of the characteristics of Popayán's road infrastructure, highlighting key aspects related to the road network, pavement condition, road safety, and other relevant elements.

1) Main Road Network

The central area of Popayán boasts a main road network that connects key points of the historic center and facilitates access to surrounding areas (GONZALEZ MARÍN , 2007). Some of the main roads in this area include:

a) Carrera 6ª: Known as one of the most important arterial roads in Popayán, Carrera 6ª traverses the city's historic center, connecting Plaza de Caldas with Plaza de Bolívar. This street is one of the busiest and is home to a variety of shops, restaurants, and historical buildings.

b) Carrera 5ª: Parallel to Carrera 6ª, Carrera 5ª is also a main road in downtown Popayán. Along this street, numerous commercial establishments, hotels, and tourist attractions can be found, such as the Church of San Francisco.

c) Carrera 4ª: Located near Caldas Park, Carrera 4ª is another important road in the central area of Popayán. It connects the historic center with residential and commercial areas, providing access to places of interest such as the Basilica Cathedral of Our Lady of the Assumption.

d) Calle 6ª: This street runs through the historic center of Popayán and is known for its cultural and commercial significance. It connects Plaza de Caldas with the Church of San Francisco and other tourist attractions.

e) Calle 4ª: Around Caldas Park, Calle 4ª is another key thoroughfare in the central area of Popayán. It connects Plaza de Bolívar with Carrera 6ª and provides access to various services and shops.

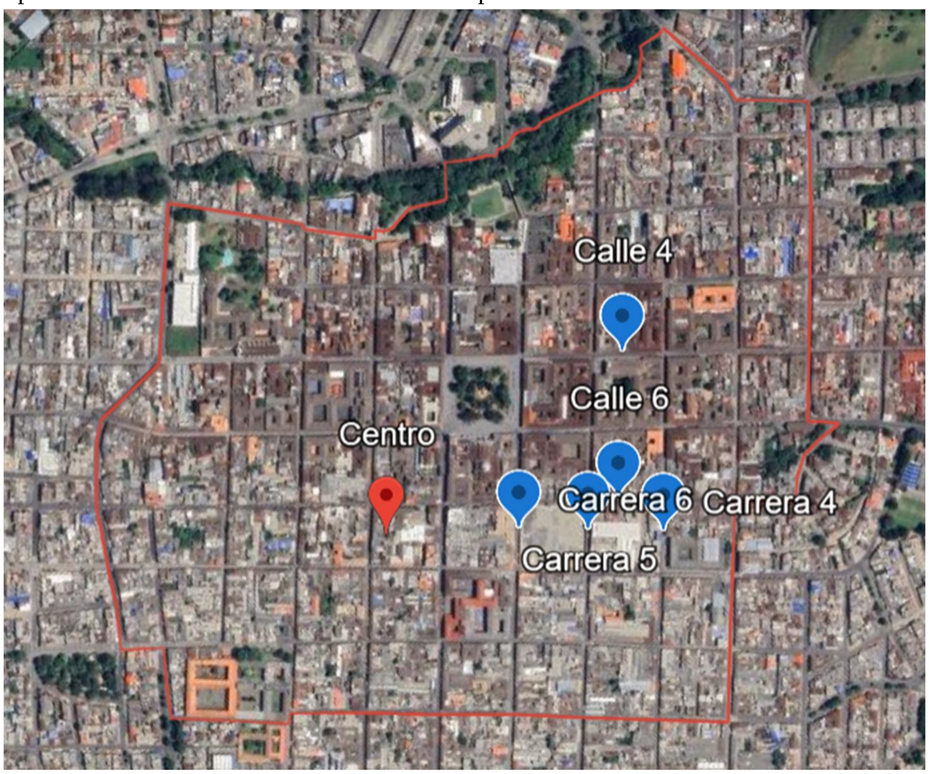

Illustration 1 SOURCE: Google Earth, Cartographic analysis of the road network in the central area of Popayán.

2) Pedestrian Traffic and Tourist Points

Plaza de Caldas, Plaza de Bolívar, and the Church of San Francisco are just a few of the tourist points and areas with high pedestrian concentration in the central area of Popayán. When designing the electric tricycle, it is essential to consider the safety of pedestrians and cyclists, as well as the need for maneuverability in congested spaces. In the central area of Popayán, Colombia, a large amount of pedestrian traffic and tourist points are concentrated due to its rich historical and cultural heritage (Popayán Travel, 2023). Some notable areas with high pedestrian traffic and tourist points include:

a) Caldas Square: Located in the heart of the historic center of Popayán, Plaza de Caldas is a popular meeting point for both residents and tourists alike. Surrounded by beautiful colonial buildings and flanked by the Church of San Francisco, the square is an iconic location where people gather to rest, socialize, and enjoy the architecture and atmosphere.

b) Church of San Francisco: This impressive church, located on Carrera 6ª near Plaza de Caldas, is one of the main points of historical and architectural interest in Popayán. Built in the 16th century, the church features an elaborate Baroque facade and an interior adorned with religious artworks. It attracts numerous visitors interested in the history and culture of the region.

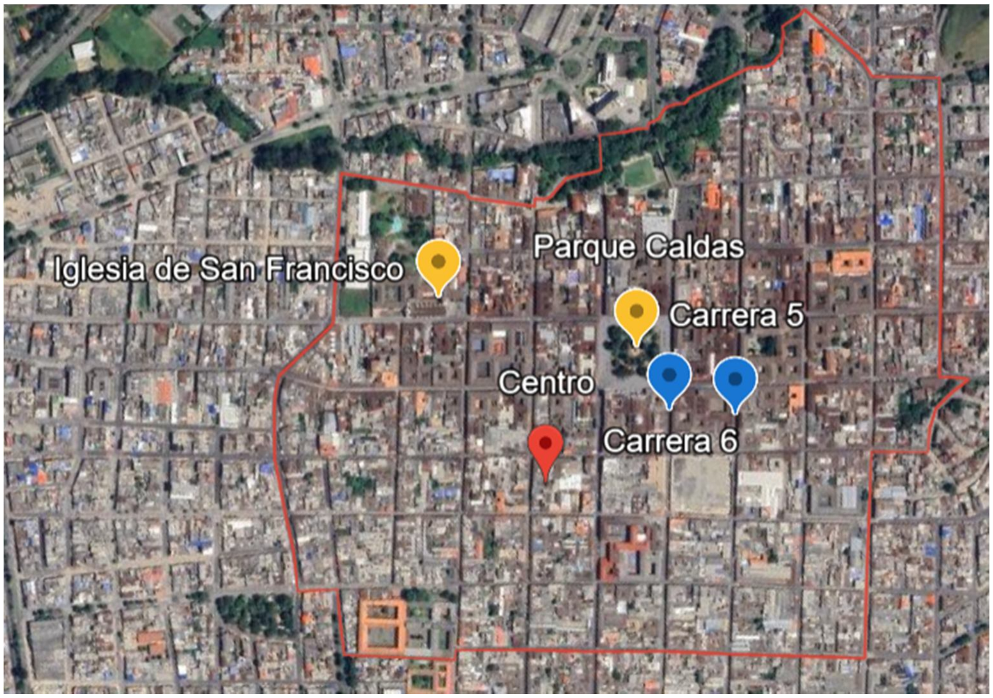

Illustration 2 SOURCE: Google Earth Cartographic Analysis of Tourist Points in the Historic Center of Popayán..

3) Distribution and Density of Road Network

The distribution and density of the road network in the downtown area of Popayán, Colombia, is a topic of crucial importance in the context of urban development and transportation planning. This area, characterized by its historical and cultural richness, hosts a complex network of streets and roads that connect key points of the historic center and facilitate access to residential, commercial, and tourist areas. In this essay, we explore the distribution and density of the road network in the downtown area of Popayán, as well as its impact on urban mobility and the quality of life of its inhabitants. The distribution of the road network in the downtown area of Popayán is characterized by the presence of narrow and cobblestone streets that reflect its colonial heritage. One of the most representative roads is the well-known 'Calle Real,' a historic artery that runs through the heart of the historic center. Calle Real, with its cobblestone pavement and colonial architecture, is a symbol of Popayán's cultural identity and an important route for traffic flow and pedestrians in the area.

In addition to Calle Real, other significant streets in the distribution of the road network include Carrera 6ª and Carrera 5ª, which connect emblematic squares such as Plaza de Caldas and Plaza de Bolívar. These streets, although picturesque, may present challenges for vehicular circulation due to their narrowness and winding nature. However, they also contribute to the city's unique and charming character (GONZALEZ MARÍN , 2007).

In terms of density, the road network in the downtown area of Popayán tends to be more compact and congested compared to other areas of the city. The presence of historical buildings and limited public spaces has resulted in a higher concentration of traffic and pedestrians on these narrow streets. This can lead to traffic congestion during peak hours and difficulties in parking, especially in areas with high tourist traffic.

The distribution and density of the road network also have a significant impact on urban mobility and the quality of life of residents in the downtown area of Popayán. On one hand, limited accessibility and congestion can hinder the efficient movement of citizens, especially those reliant on public transportation or pedestrian mobility. On the other hand, preserving the historic road infrastructure is crucial for maintaining the city's cultural heritage and attracting tourism, which in turn contributes to the local economy.

To address the challenges associated with the distribution and density of the road network in the downtown area of Popayán, it is necessary to implement urban planning strategies and transportation management. These may include measures to improve road infrastructure, such as widening sidewalks, creating pedestrian zones, and optimizing public transportation routes. Additionally, it's important to encourage the use of alternative modes of transportation, such as cycling and ride-sharing, to reduce congestion and promote environmental sustainability.

a) Fast Traffic: During the early morning and late evening hours, traffic in the downtown area is generally fast. During these periods, there are fewer vehicles on the streets, allowing for more efficient and uninterrupted movement.
b) Slow Traffic: During certain hours of the day, such as the early afternoon, traffic is slower. Although not as smooth as fast traffic, vehicles can still move without significant delays.
c) Moderate Traffic: During midday hours, vehicular flow tends to be moderate. Although some delays may still occur, mobility improves considerably compared to peak hours. Wait times are shorter, and traffic is smoother.
d) Slow Traffic: During peak commercial and school activity hours, traffic in downtown Popayán tends to be slow. Vehicle speeds decrease significantly due to high traffic density and frequent stops.
e) Very Slow Traffic: During peak hours, especially in the morning and late afternoon, traffic in certain areas of the downtown area is extremely dense. This results in very slow vehicle speeds, frequent stops, and significant congestion.

4) Critical Point: Calle 4

The specific analysis of traffic on different streets in downtown Popayán identified Calle 4 as one of the roads with the highest congestion. Calle 4 experiences particularly heavy traffic during peak hours due to its role as a main artery connecting several important areas of the city. This congestion is attributed to a combination of factors, including high vehicle density, the convergence of public and private transportation routes, and the presence of key intersections that slow down traffic flow (Alcaldia de Popayan , 2023).

5) Pavement Condition:

The pavement condition in the Historic Center of Popayán varies depending on the area. While some streets have been recently paved or cobblestoned, others show considerable deterioration due to the passage of time, constant use, and lack of proper maintenance (Alcaldia de Popayan , 2023). Potholes, cracks, and uneven surfaces in the pavement pose a risk to road safety for both pedestrians and vehicles and can affect the experience of visitors.

a) Type of Pavement and Age:

Downtown Popayán has a variety of pavement types, including cobblestones (stone-paved streets), asphalt, and concrete.

- Level of Deterioration: Technical reports and academic studies agree that the overall condition of the pavement in downtown Popayán is deficient. A series of problems are observed, such as potholes, cracks, sinkholes, and deformations. These issues are more severe on streets with higher vehicular and pedestrian traffic.(Periodico Virtual, 2023)..

b) Impact on the Community:

Surveys of residents and merchants revealed that the poor condition of the pavement has a negative impact on the community's quality of life. Residents report issues such as difficulty walking, excessive noise, and damage to their vehicles. Merchants also note that the poor condition of the pavement negatively affects their businesses, as it discourages customers from visiting their establishments.

c) Causes of Pavement Deterioration:

The causes of pavement deterioration in the central area of Popayán are diverse and include:

- Lack of Maintenance: The lack of preventive and corrective maintenance by municipal authorities has contributed to pavement deterioration (Alcaldia de Popayán, 2022).
- Weather Conditions: Heavy rains and sudden temperature changes are factors that accelerate pavement deterioration.
- Vehicle Load: The increase in vehicular traffic in the central area, especially heavy vehicles, has exerted significant pressure on the pavement(Alcaldia de Popayán, 2022).

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d) Infrastructure Works

He constant infrastructure works in the downtown area, such as the installation of pipelines and the construction of buildings, have also contributed to the deterioration of the pavement.

It is important to highlight that the preservation of the historical heritage of the Historic Center demands a balance between the functionality of the road infrastructure and the conservation of the original elements. Maintenance and rehabilitation interventions must be carried out carefully, using materials and techniques compatible with the aesthetics and authenticity of the place.

An exhaustive study of vehicular flow in downtown Popayán was conducted using Google Maps. This tool allowed for the analysis of traffic patterns at different times of the day, identifying areas with the highest congestion. By evaluating real-time data and historical data provided by Google Maps, critical points where traffic is most intense could be determined.

Table 1 SOURCE: Own Elaboration (Excel), Traffic Classification by Colors

Fast	
Slow	
Moderate	
Slow	
Very Slow	

Table 2 SOURCE: Own Elaboration (Excel), Traffic Classification in Downtown Popayán

VEHICULAR FLOW						
HOUR (24 H)	Street 4	Street 5	Avenue 9	Avenue 8	Avenue 4A	Avenue 3
9:24						
10:42						
11:59						
12:29						
14:49						
5:40						
6:50						

The study of vehicular flow in downtown Popayán, conducted using Google Maps, revealed significant variability in traffic levels throughout the day. The data obtained allowed for the classification of traffic into five levels: fast, slow, moderate, slow, and very slow. This analysis showed that traffic in downtown Popayán can vary drastically in short periods of time.

6) Signage and Road Safety Devices:

Road signage in the Historic Center of Popayán is generally adequate, including traffic signs, traffic lights, crosswalks, and road markings (Mayor's Office of Popayán, 2020). However, there are some areas where signage is insufficient or poorly visible, which can pose a risk to road safety, especially for pedestrians and tourists (Rodríguez & Flórez, 2019). Road signage in the downtown area of Popayán has some deficiencies that could impact road safety. It was observed that:

a) Lack of horizontal signage: In some streets, horizontal signage such as road markings is worn out or missing, which hampers the movement of vehicles and pedestrians.

b) Inadequate vertical signage: Some vertical signs, such as stop signs and yield signs, are poorly placed or in poor condition, which could cause confusion among road users.

c) Lack of informative signage: There aren't enough informative signs observed, such as those indicating street names or traffic directions.

7) Road Safety Devices

The downtown area of Popayán has some road safety devices such as traffic lights, speed bumps, and crosswalks. However, some deficiencies in their operation and condition were observed:

a) Outdated traffic lights: Some traffic lights lack the appropriate technology to efficiently regulate vehicular traffic, leading to congestion and increased accident risks.
b) Ineffective speed bumps: Some speed bumps are poorly designed and placed, rendering them ineffective in slowing down vehicles.
c) Poorly maintained crosswalks: Some crosswalks are deteriorated or lack proper signage, jeopardizing pedestrian safety.

Signage should be tailored to the characteristics of the Historic Center, using designs and materials that blend with the aesthetics of the area. Additionally, it's important to implement traffic control measures such as low-emission zones or pedestrian zones to ensure the safety of vulnerable users and preserve the historical heritage

8) Pedestrian and Cyclist Infrastructure:

Popayán has sidewalks on most streets and avenues, providing safe spaces for pedestrian traffic. Additionally, bike lanes have been implemented in some areas of the city, although their coverage is still limited.

The downtown area of Popayán has some sidewalks for pedestrians (Vialco Ingeniería Vial & Movilidad., 2024), but they have some deficiencies that could affect pedestrian safety and comfort. It was observed that:

a) Poorly maintained sidewalks: Some sidewalks are deteriorated, with potholes, cracks, and uneven surfaces, making it difficult for pedestrians to circulate, especially for individuals with reduced mobility.
b) Insufficiently wide sidewalks: In some streets, sidewalks are too narrow, forcing pedestrians to walk on the road, exposing them to accident risks.
c) Lack of access ramps: In some areas, there are no access ramps for people with reduced mobility, preventing them from accessing sidewalks and buildings.
d) Lack of pedestrian signage: There aren't enough pedestrian signs, such as those indicating pedestrian crossings or the presence of cyclists.

9) Cyclist Infrastructure

The downtown area of Popayán does not have a complete network of bike lanes, which makes it difficult and discourages the use of bicycles as a means of transportation. It was observed that:

a) Discontinuous bike lanes: Existing bike lanes are discontinuous or not adequately marked, causing confusion among cyclists and vehicle drivers.
b) Poorly maintained bike lanes: Some bike lanes are deteriorated, with potholes, cracks, and uneven surfaces, making them dangerous for cyclists.
c) Lack of connection between bike lanes: There is no proper connection between existing bike lanes, making it difficult for cyclists to travel through the downtown area safely and efficiently.Intersecciones y Cruces:

Intersections and road crossings in Popayán vary in their design and functionality. Some intersections are equipped with traffic lights and adequate signage, while others experience congestion and pose risks to road safety, especially during peak traffic hours.

Some deficiencies were observed in the design of intersections and road crossings in the downtown area of Popayán that could affect road safety and traffic flow:

- Inadequate geometric design:Some intersections and road crossings have inadequate geometry, with very sharp turning angles or insufficient curvature radii, making it difficult for vehicles to maneuver and increasing the risk of accidents.
- Lack of turning lanes: Some intersections and crossings lack left-turn or right-turn lanes, forcing vehicles to make two-stage turns, causing congestion and increasing the risk of accidents.
- Lack of safety islands: Some intersections and crossings lack safety islands to protect pedestrians crossing the street.

10) Intersection and Crossing Signage

The signage at intersections and crossings in the downtown area of Popayán has some deficiencies that could affect road safety:

a) Outdated or poorly maintained signage: Some traffic signs are outdated or in poor condition, making it difficult for drivers to read and understand them.
b) Lack of preventive signage: Some intersections and crossings lack preventive signage warning drivers about the presence of the intersection or crossing, increasing the risk of accidents.

c) Lack of yield signage: Some intersections and crossings lack yield signage, causing confusion among drivers and increasing the risk of accidents.

11) Operation of Intersections and Crossings

The operation of intersections and crossings in the downtown area of Popayán has some shortcomings that could affect traffic flow:

a) Lack of traffic light synchronization: Some intersections and crossings do not have adequate traffic light synchronization, resulting in congestion and increased waiting time for vehicles.
b) Presence of street vendors: The presence of street vendors at intersections and crossings obstructs the visibility of drivers and pedestrians, increasing the risk of accidents.
c) Reckless driving: Reckless driving by some drivers, such as speeding or not obeying traffic signals, increases the risk of accidents at intersections and crossings

12) Parking and Public Transportation:

The city has a varied offer of both public and private parking lots, although they can be scarce in central areas. Regarding public transportation, Popayán has a network of urban buses covering a large part of the urban area, providing mobility options for citizens. The downtown area of Popayán has a limited supply of parking spaces, causing difficulties for drivers looking for a place to park their vehicles. It was observed that:

a) Limited availability of parking spaces: The number of parking spaces available in the downtown area is insufficient to meet the demand of users.
b) High prices: The prices of public parking lots are high, which discourages their use.
c) Poor condition of parking lots: Some public parking lots are in poor condition, with deteriorated pavement, poor lighting, and lack of security.
d) Lack of parking spaces for people with disabilities: There aren't enough parking spaces for people with disabilities in the downtown área.

13) Public Transportación

Public transportation in the downtown area of Popayán has some deficiencies that affect the comfort and satisfaction of users. It was observed that:

a) Obsolete bus fleet: The majority of the public transportation bus fleet is obsolete, with units that are in poor condition and do not offer basic amenities for users.
b) Incomplete routes: Public transportation routes do not cover all areas of the city, making it difficult to access some places.
c) Low frequencies: Bus frequency is low, especially during peak hours, resulting in long waiting times for users.
d) Lack of information: There is insufficient information about routes, schedules, and fares of public transportation at bus stops

Improving parking and public transportation in downtown Popayán is crucial to ensure traffic flow, user convenience, and environmental sustainability. Implementing the recommended measures from this analysis will help create a more accessible, inclusive, and sustainable city.

Furthermore, an exhaustive investigation was conducted, detailed data on bus routes and other public transportation modes operating in the city were collected. These data were visually represented using georeferenced maps, which allow for a more intuitive and accurate understanding of service coverage. Below are examples of maps illustrating the main routes passing through downtown Popayán

Illustration 3 SOURCE: Google Earth, Cartographic Analysis of Public Transportation Routes by Transpubenza Company The previous illustration shows the streets and avenues through which the public system of the Transpubenza company has access, highlighting how it utilizes some of the main thoroughfares. The routes that cover these sections are:

- TP2M
- TP7M
- TP9M
- TP11M

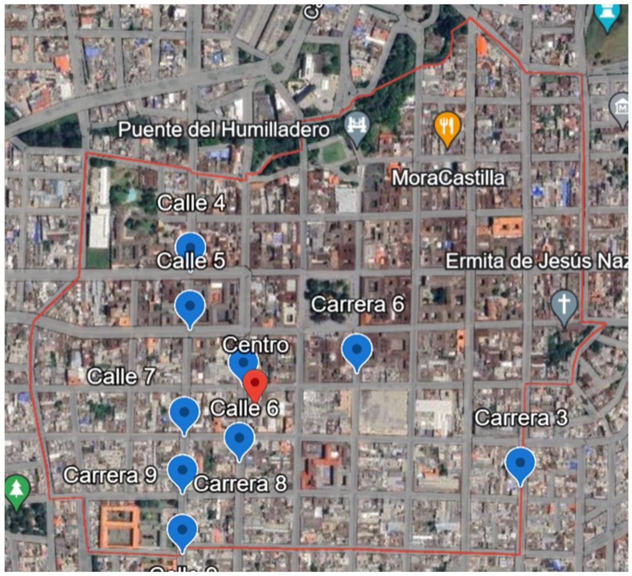

Illustration 4 Google Earth, Cartographic Analysis of Public Transportation Routes by Sotracauca Company

The previous illustration depicts the streets and avenues through which the public transportation system of the Sotracauca company has access, highlighting its utilization of some of the main thoroughfares. The routes covering these sections are:

- SC5M
- SC7M
- SC8M

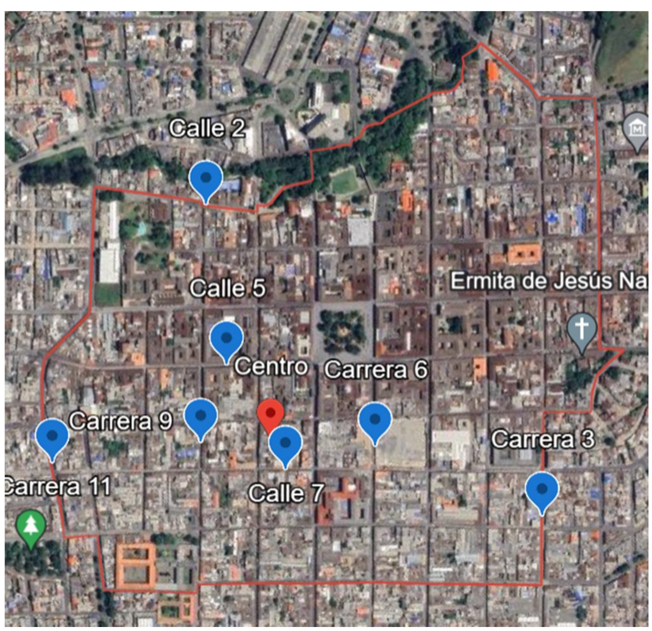

Illustration 5 Google Earth, Cartographic Analysis of Public Transportation Routes by Translibertad Company

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The previous illustration shows the streets and avenues through which the public transportation system of the Translibertad company has access, highlighting its utilization of some of the main thoroughfares. The routes covering these sections are:

- TL1M
- TL2BT
- TL2M
- TL3BT
- TL4BT
- TL5M
- TL6BT

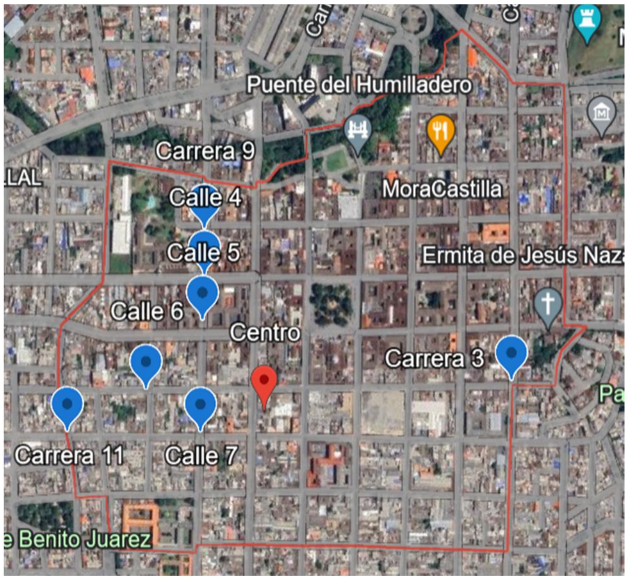

Ilustración 6 Google Earth, Análisis Cartográfico de las Rutas de Transporte Público de la Empresa Translibertad

The illustration above shows the streets and avenues through which the public system of the company Transtambo has access, highlighting how it utilizes some of the main roads. The routes that cover these sections are:

- TT2M
- TT4M
- TT5M

B. STAGE II

The logistics of collecting recyclable solid waste in Popayán faces several significant challenges that affect both the efficiency and effectiveness of the process. The collectors, many of whom are affiliated with the Sorting and Recycling Stations (ECA), use a variety of vehicles ranging from more formal options to improvised solutions. The types of vehicles include:

1) Cargo Vehicles: Used by some collectors, these vehicles allow for the transportation of larger volumes of waste. However, their use is limited by road conditions and accessibility in certain areas of the city center.
2) Cargo Motorcycles: They offer better maneuverability on narrow and congested streets, but have a more limited loading capacity compared to cargo vehicles. Despite their versatility, handling the maximum load they can carry remains a challenge.
3) Handcarts: Commonly used by individual collectors, handcarts are a cost-effective option but require considerable physical effort and have a very limited loading capacity. These limitations make handcarts less efficient for long distances or for collecting large volumes of waste.
4) Homemade Vehicles: These vehicles, handmade or modified from others, reflect the lack of resources and technological support. Their non-optimized design reduces efficiency and increases physical strain on the collectors. Often, these vehicles are not designed to withstand the weight and volume of waste that needs to be collected, leading to longer collection times and increased wear and tear.

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a) Lack of Order and Coordination

One of the main features of the current logistics is the disorganization in the collection routes. There's no established order, resulting in disorganized routes and prolonged collection times. This lack of structure hinders efficient coverage and contributes to waste accumulation in certain areas. The absence of a data-based management and planning system leads collectors to make intuitive decisions without a clear guide to optimize their routes.

b) Integration with URBASER Routes

The recyclable solid waste collectors also take into account the routes of the company URBASER, a specialized environmental management company focused on urban services. The collectors aim to cover the areas where URBASER operates, conducting their route approximately 20 minutes before the company's vehicles arrive. This strategy allows them to collect recyclable materials that might otherwise be taken to the landfill by URBASER. However, this practice adds an additional layer of complexity and pressure to the process, as the collectors must synchronize their activities with the schedules and routes of another company, often without direct communication or formal coordination. The sense of the streets in the downtown area will now be evidente:

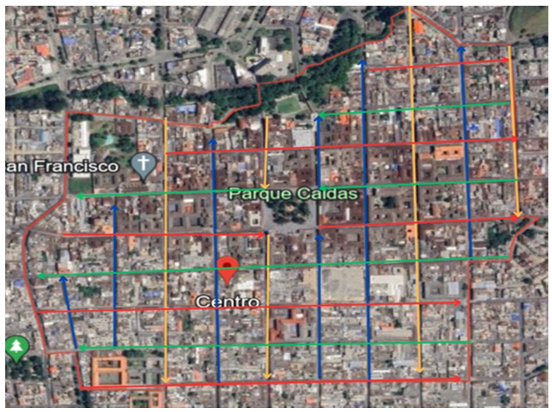
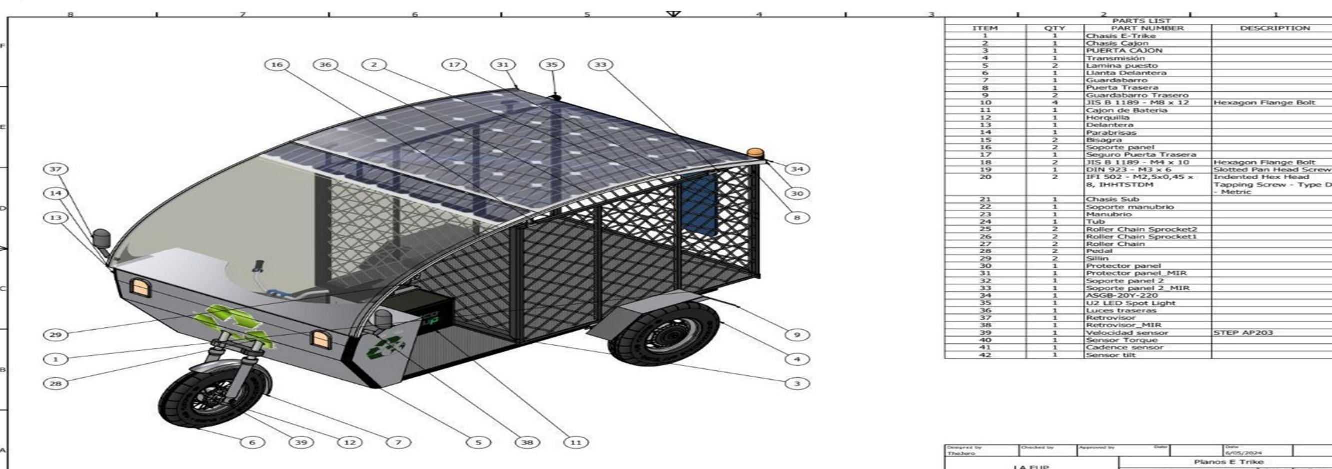


Ilustración 7 Google Earth, Cartographic Analysis of the Directions of the Roads in the Downtown Area of Popayán

c) Work Conditions and Efficiency

The work conditions of the collectors also pose a significant challenge. The use of non-optimized vehicles and the absence of mechanical assistance mechanisms increase the physical burden on the collectors, which can lead to occupational health problems and lower efficiency in waste collection. Without proper planning and the necessary technology to facilitate the process, collectors often spend more time and effort than necessary on waste collection, reducing the amount of recyclable materials recovered and increasing fatigue.

C. STAGE III



ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Chasis E-Trike	
2	1	Chasis Cajon	
3	1	PUERTA CAJON	
4	1	Transmisión	
5	2	Lamina puesto	
6	1	Llanta Delantera	
7	1	Guardabarro	
8	1	Puerta Trasera	
9	2	Guardabarro Trasero	
10	4	JIS B 1189 - M8 x 12	Hexagon Flange Bolt
11	1	Cajon de Bateria	
12	1	Horquilla	
13	1	Delantera	
14	1	Parabrisas	
15	2	Bisagra	
16	2	Soporte panel	
17	1	Seguro Puerta Trasera	
18	2	JIS B 1189 - M4 x 10	Hexagon Flange Bolt
19	1	DIN 923 - M3 x 6	Slotted Pan Head Screw
20	2	IFI 502 - M2,5x0,45 x 8, IHHTSTDM	Indented Hex Head Tapping Screw - Type D - Metric
21	1	Chasis Sub	
22	1	Soporte manubrio	
23	1	Manubrio	
24	1	Tub	
25	2	Roller Chain Sprocket2	
26	2	Roller Chain Sprocket1	
27	2	Roller Chain	
28	2	Pedal	
29	2	Sillin	
30	1	Protector panel	
31	1	Protector panel_MIR	
32	1	Soporte panel 2	
33	1	Soporte panel 2_MIR	
34	1	ASGB-20Y-220	
35	1	U2 LED Spot Light	
36	1	Luces traseras	
37	1	Retrovisor	
38	1	Retrovisor_MIR	
39	1	Velocidad sensor	STEP AP203
40	1	Sensor Torque	
41	1	Cadence sensor	
42	1	Sensor tilt	

SOURCE: INVENTOR, General Plans of the E-Trike Cargo Design

Detailed Design of the Electric Cargo Tricycle

1) *Chassis and Structure*

a) *Carbon Fiber and Stainless Steel Chassis:*

Functionality: Provides the main structure of the tricycle, combining lightness and strength to support the load and electrical components. The carbon fiber reduces the overall weight of the vehicle, while the stainless steel offers durability and corrosion resistance, crucial for the longevity of the tricycle in varied urban conditions.

2) *Propulsion System*

a) *Raizo Chen Motor Pedelec Electric Bike Conversion Kit:*

Functionality: The integrated motor assists pedaling by detecting pedal movement and providing additional power to facilitate the transport of heavy loads. This system includes an intelligent controller that optimizes motor power according to the terrain and load requirements.Transmisión de Cuatro Piñones:

Functionality: The gear system allows for adjusting the transmission ratio, making pedaling easier and enhancing motor efficiency under various load and terrain conditions. The sprockets are designed to withstand high loads and provide smooth, precise shifting.

b) *Motorcycle Chain:*

Functionality: Transmits the power from pedaling and the motor to the rear wheels, ensuring a robust and durable connection. This chain is wear-resistant and designed for high-tension conditions.

3) *Power System*

a) *Solar Charge Battery Controller 80A PWM 12V-48V Lithium Bulk/B:*

Functionality: Controls the battery charging via the solar panel, ensuring efficient charging and protecting the battery from overcharging. This controller includes protection against overcharge, overheating, and short circuits.Batería de Litio LiFePO4 de 36 V/43.8 V 8 A, Cargador Inteli:

Functionality: Main power source for the motor and electrical components of the tricycle. The LiFePO4 lithium battery is known for its high energy density and long lifespan, capable of enduring multiple charge and discharge cycles without significant capacity loss.

b) *Renogy LTWT-Flex - 100W Solar Panel, 12V:*

Functionality: Provides additional solar power to charge the battery while the tricycle is in use or parked, extending its range and reducing dependence on the electrical grid. This panel is flexible and lightweight, allowing for easy integration into the tricycle's design..

4) *Sensor Systems*

a) *Bosch Wheel Speed Sensor:*

Functionality: Monitors the tricycle's speed to optimize motor assistance and provide precise data for navigation and control. These data can also be used for efficiency analysis and preventive maintenance.

b) *Bafang Torque Sensor TMM4:*

Functionality: Measures the force applied to the pedals to adjust motor assistance based on the cyclist's effort, enhancing efficiency and the riding experience. This sensor is crucial for providing natural and smooth assistance.

c) *Garmin Cadence Sensor 2:*

Functionality: Measures pedaling frequency to adjust motor assistance and optimize performance. This helps maintain a constant cadence and reduce cyclist fatigue.

d) *Bosch Inclinometer Sensor:*

Functionality: Detects terrain inclination to adjust motor power on slopes, making pedaling easier on hills. This sensor enhances tricycle safety and control on uneven terrain.

e) Temperature Sensor NTC 10K:

Functionality: Monitors the temperature of electrical components to prevent overheating and ensure safe and efficient operation. This sensor is essential for battery and motor protection.

f) STMicroelectronics LIS3LV02DL Inclinometer Sensor:

Functionality: Provides precise data on terrain inclination for fine adjustments in motor assistance and tricycle stability

5) Comfort and Safety Components

a) Electric Tricycle Seat with Backrest:

Functionality: Provides additional comfort for the cyclist during long periods of use, improving ergonomics and reducing fatigue. The backrest is adjustable to accommodate different users.

b) Laminated Glass Windshield:

Functionality: Protects the rider from the elements (wind, rain, dust) while providing a clear and safe view. Laminated glass is impact-resistant, enhancing safety.

6) Suspension and Steering System

a) Coil Spring Shock Absorber:

Functionality: Absorbs impacts and terrain vibrations, enhancing the comfort and stability of the tricycle. This shock absorber is designed to withstand heavy loads and mixed terrain conditions.

b) Conventional Telescopic Fork Shock Absorber:

Functionality: Provides additional suspension on the front wheel, increasing handling capability and comfort on uneven terrain.

c) Scissor Steering:

Functionality: Steering system that allows for precise and smooth control of the tricycle, facilitating maneuvers in tight spaces and at low speeds.

7) Tires

Schwalbe Marathon Plus Cargo:

Functionality: Specifically designed for heavy loads, these tires come with puncture protection and high durability, suitable for mixed surfaces. With a recommended pressure of between 40 and 45 psi, these tires optimize traction and comfort.

8) Monitoring and Communication Systems

a) Outdoor LoRaWAN® Gateway UG67:

Functionality: Enables long-distance communication and monitoring of tricycle data, facilitating vehicle management and maintenance. This gateway is resistant to adverse environmental conditions.

b) Aeroqual Series 500 Monitor (S-500) with Sensor Head:

Functionality: Air quality monitoring device that can be used to measure pollutants during tricycle operation, contributing to environmental studies.

c) Plug-in Temp & RH Sensor:

Functionality: Monitors temperature and relative humidity, providing environmental data that can be useful for cargo management and tricycle maintenance..

9) Load Components

a) Cargo Drawer with Welded Mesh:

Functionality: Robust and secure storage space for cargo, with good ventilation and easy access. The welded mesh provides durability and allows viewing of the drawer's contents for better organization and access.

The E.Trike Cargo combines lightweight and sturdy materials, a pedal-assisted propulsion system, comfort and safety components, and advanced monitoring and communication systems. With the ability to adapt to various terrain conditions and carry heavy loads, this design is optimized to provide an efficient and sustainable solution for urban transportation in Popayán. The integration of advanced technologies and high-quality materials ensures that the tricycle is not only functional and efficient but also durable and capable of operating in a variety of urban and environmental conditions.

To calculate the total weight resistance of the electric cargo tricycle, we first need to calculate the different forces acting on it. We will use the following formulas:Fuerza de la gravedad: $Fgra$

Friction Force: $Ffriccion = \mu \cdot N$ (Halliday, Resnick, & $vedad = m \cdot g$

- Walker, 2018)
- Aerodynamic Drag Force: $Farrastre = 0.5 \cdot \rho \cdot A \cdot Cd \cdot v$^2 (Meriam, 2020)
- Aerodynamic Drag Force: 1. $Farrastre = 12 \cdot \rho \cdot A \cdot Cd \cdot v2$ (White, 2016)
- Rolling Resistance Force: $Frodar = Crr \cdot N$Donde: $Farrastre = 12 \cdot \rho \cdot A \cdot Cd \cdot v2$ (White, 2016)

- m is the total mass of the tricycle and the cargo (in kg).
- g is the acceleration due to gravity (approximately 9.8 m/s^2).
- μ is the coefficient of friction between the tires and the road surface.
- N is the normal force on the tires.
- ρ is the density of air (in kg/m^3).
- A is the frontal area of the tricycle (in m^2).
- Cd is the coefficient of aerodynamic drag.
- v is the velocity of the tricycle (in m/s).
- Crr is the coefficient of rolling resistance.Primero, calculemos la fuerza de la gravedad:

$Fgravity$ = (680 kg + 300 kg) · 9.8 m/s^2

$Fgravity$ = 9800 N

Now, let's calculate the normal force on the tires. Since the tricycle is in equilibrium, the normal force is equal to the total weight:

N=9800 N

Next, let's calculate the frictional force. We'll take the worst-case scenario, which is when the road surface has a coefficient of friction of 0.8:

Friction force = 0.8 * 9800 N

Friction force = 7840 N

Then, let's calculate the aerodynamic drag force. We'll use the formula for aerodynamic drag:

$Farrastre = 12 \cdot \rho \cdot A \cdot Cd \cdot v2$

First, we need to define the average values for the air density and the coefficient of aerodynamic drag. According to typical data, the air density (ρ) is around 1.2 kg/m^3 and the coefficient of aerodynamic drag (Cd) for a standard vehicle is approximately 0.3.

Given that we're using the average values for air density (ρ = 1.2 kg/m^3) and the coefficient of aerodynamic drag (Cd = 0.3), we can calculate the aerodynamic drag force (F_aero) using the formula:

Faero=1/2$\cdot \rho \cdot A \cdot Cd \cdot v2$

where:

- ρ is the air density.
- A is the frontal area of the tricycle.
- Cd is the coefficient of aerodynamic drag.
- v is the velocity of the tricycle.

Faero≈101.25 N

This value is consistent with the expected aerodynamic resistance for an electric cargo tricycle moving at a speed of 25 km/h under normal city conditions. Finally, let's calculate the rolling resistance force. We'll use the worst-case scenario, which is when the road surface has a coefficient of rolling resistance of 0.8:

$Frodar$=0.8*9800 N

$Frodar$=7840 N

This value represents the resistance that the electric tricycle faces due to the friction of the tires with the road surface. Although it's slightly higher than the value calculated for Cr=0.5, it still falls within an expected range for a tricycle of this type and weight.

Now, we can calculate the total weight resistance by summing up all these forces:

Ftotal ≈ 7840 N +101.25 N + 7840 N

Ftotal≈15061.25N

This is the total force that the electric tricycle's motor must overcome to maintain a constant speed of 25 km/h under slightly higher rolling resistance conditions. Although it's higher than the value calculated for Cr=0.5, it still falls within a reasonable range for this type of vehicle.

The implementation of last-mile logistics in the collection of recyclable solid waste in the city of Popayán in the central area represents a key opportunity to improve the efficiency and effectiveness of this process. Here are some ways in which last-mile logistics could specifically adapt to the needs:

Utilizing route optimization technology, collection vehicles could plan and execute more efficient routes for collecting recyclable solid waste from households and businesses in the city. This would help reduce travel times, operating costs, and carbon emissions.

 Geographic Information Systems (GIS) GIS allows for the collection, storage, analysis, and presentation of geospatial data. With proper GIS, waste generation patterns in a city can be visualized and analyzed, aiding in planning more efficient collection routes (Bosque , 2014)..

Several companies have successfully applied Geographic Information Systems (GIS) in a variety of industries. Some examples include:

- Amazon: Uses GIS to plan and optimize package delivery routes, allowing them to minimize delivery times and logistical costs .
- Uber: Uses GIS to efficiently assign drivers to passengers, optimizing routes and reducing wait times.
- FedEx: Uses GIS to track and manage shipments in real-time, as well as to plan and optimize package delivery routes.
- Walmart: Uses GIS to analyze customer purchasing patterns and optimize product layouts in their stores, allowing them to improve customer experience and increase sales.
- Telefónica: Uses GIS to plan and manage telecommunications infrastructure, such as mobile phone towers and fiber optic cables, allowing them to improve coverage and service quality.

 Route Optimization Algorithms These algorithms are designed to calculate the best sequence of stops to minimize the total distance traveled by collection vehicles. Algorithms such as the nearest neighbor algorithm, the time-saving algorithm, and the genetic algorithm are examples of approaches that can be used to optimize collection routes.

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2) Route Optimization Algorithms

These algorithms are designed to calculate the best sequence of stops to minimize the total distance traveled by collection vehicles. Algorithms such as the nearest neighbor algorithm, the time-saving algorithm, and the genetic algorithm are examples of approaches that can be used to optimize collection routes.

Nearest Neighbor Algorithm: This algorithm starts at an initial point and selects the nearest point as the next destination. It then moves to the next nearest point and repeats the process until each point is visited once. Although it does not guarantee the most optimal route, it is fast and easy to implement, making it useful for problems with a large number of locations.

- Traveling Salesman Problem (TSP): It is one of the classic combinatorial optimization problems. The goal is to find the shortest route that visits each of a set of locations exactly once and returns to the starting point. Several approaches have been developed to solve this problem, including exact algorithms (such as dynamic programming and branch and bound) and heuristics (such as the genetic algorithm and tabu search).
- Time-Saving Algorithm: This algorithm is commonly used in vehicle route optimization. It involves merging two routes into a single route, taking advantage of time savings obtained by eliminating or reducing distances compared to individual routes. The process is repeated until no additional savings can be obtained.
- Genetic Algorithms: These algorithms are inspired by the process of natural selection and biological evolution. They use a population of candidate solutions (routes in this case) and apply genetic operators such as selection, recombination, and mutation to generate new solutions. The fittest individuals (those with the shortest distance routes) are more likely to survive and reproduce, leading to convergence towards optimal or near-optimal solutions.
- Ant Colony Optimization (ACO): Inspired by the behavior of ant colonies, this algorithm simulates how ants find the shortest path between a food source and their nest. Ants deposit pheromones on the ground as they explore different routes, and the pheromones attract other ants towards the shortest routes. Over time, routes with higher amounts of pheromones are reinforced, leading to convergence towards an optimal solution.

These are some companies that employ different route optimization algorithms in their operations:

- Amazon: Utilizes route optimization algorithms such as the nearest neighbor algorithm and the genetic algorithm in its delivery network to optimize driver routes and minimize delivery times.
- Uber: Employs route optimization algorithms to efficiently assign drivers to passengers and calculate the shortest and fastest routes for trips, thereby optimizing the efficiency of the transportation service.
- FedEx: Utilizes route optimization algorithms such as the traveling salesman problem algorithm and the time-saving algorithm to plan and execute package delivery routes, minimizing travel times and operational costs.
- Google Maps: Employs various route optimization algorithms in its mapping application to calculate the best routes for users, taking into account factors such as real-time traffic, distance, and travel duration.
- UPS: Utilizes route optimization algorithms in its delivery network to efficiently plan and execute driver routes, minimizing delivery times and operational costs.

These are just some of the companies that employ route optimization algorithms in their operations to improve efficiency and the quality of service they offer to their customers. Many other companies in various industries, such as logistics, transportation, e-commerce, and technology, also make use of these algorithms to optimize their processes and enhance their competitiveness in the market.

3) Sensors and IoT Devices

Installing sensors on waste containers and collection vehicles can provide real-time data on the fill level of the containers and the location of the vehicles. This data can be used to optimize collection routes and schedule collection only when necessary, thereby reducing travel times and operational costs.

For last-mile logistics systems aimed at collecting recyclable solid waste, specific sensors and IoT devices are required that can efficiently monitor and optimize the collection of these materials. Here are some types of sensors and IoT devices tailored for these systems:

- Waste container fill level sensors: These sensors can be installed on waste containers to monitor the fill level. When a container reaches its maximum capacity, the sensor can send an alert to the control center, enabling timely and efficient collection (Guillermo Sánchez-Díaz, 2013).
- Weight sensors in waste containers: These sensors can detect the weight of solid waste deposited in the containers. This information can be used to plan the collection and transportation of waste (Pedregal, 2003), ensuring that containers are emptied when necessary.
- Waste sorting sensors: These sensors can automatically identify the types of solid waste deposited in the containers, such as paper, plastic, glass, or metal. This information is useful for planning the separation and processing of waste efficiently ·(García-Nájera, 2008).
- GPS tracking devices in collection vehicles: These devices allow real-time tracking of the location of collection vehicles, facilitating route planning and coordination of collection operations.
- Communication and fleet management devices: These devices enable two-way communication between collection vehicle drivers and the control center. This facilitates the coordination of collection activities, route assignment, and real-time problem resolution.
- Radio-frequency identification (RFID) devices: These devices can be used to label and track waste containers and other equipment used in the collection process. This helps maintain accurate records of assets and prevent theft or loss of equipment.
- Temperature and humidity sensors: These sensors can monitor environmental conditions inside waste containers, ensuring that solid waste remains in optimal conditions during transportation and storage.

These are some of the sensors and IoT devices specifically tailored for last-mile logistics systems aimed at collecting recyclable solid waste. The combination of these devices can significantly improve the efficiency and effectiveness of recyclable solid waste collection operations.

Several companies worldwide have implemented IoT technology in their last-mile logistics systems for the collection of recyclable solid waste. Here are some examples:

- Waste Management: A Houston, Texas-based American company, Waste Management is one of the largest waste management companies in the world. They have implemented IoT sensors in their waste containers to monitor container fill levels and optimize collection routes. They use GPS tracking technology in their collection vehicles for more efficient fleet management.
- Veolia: A French company headquartered in Paris, Veolia is a leading waste management company that has used IoT technology in its waste collection systems to improve efficiency and sustainability. They have implemented fill sensors in waste containers and waste sorting sensors to facilitate the separation and processing of recyclable materials..
- Suez: Another French company, headquartered in Paris, Suez is a global environmental services company that has adopted IoT technology in its waste management operations. They use IoT sensors in waste containers and collection vehicles to monitor container fill levels and optimize collection routes, thereby reducing operational costs and carbon emissions.
- Covanta: An American company based in Morristown, New Jersey, Covanta is a leading waste management and energy-from-waste company. They have implemented IoT technology in their waste processing plants to remotely monitor and control the incineration process and energy generation, thereby optimizing operational efficiency and reducing environmental impacts.

These are just a few examples of companies that have used IoT technology in their last-mile logistics systems for the collection of recyclable solid waste. The adoption of this technology is increasing in the waste management industry as it helps improve efficiency, reduce operational costs, and minimize the environmental impact of waste collection and processing operations.

Last-mile logistics allows for more dynamic scheduling of recyclable solid waste collections. Fleet management systems could adjust routes and schedules in real-time based on factors such as traffic, weather conditions, and the availability of full containers.

4) Fleet Management Systems (FMS)

These systems allow real-time monitoring and management of a fleet of collection vehicles. FMS can integrate with route optimization algorithms to provide real-time instructions to drivers on the best route to take, taking into account real-time traffic and road conditions (Navas Lanchas, 2014). Fleet Management Systems (FMS) used in various industries:

- Fleet Complete: It's a fleet management system used in several industries, including transportation, delivery services, construction, and utilities. It provides real-time vehicle tracking, data analysis, route scheduling, maintenance alerts, and driver management.
- Verizon Connect: Formerly known as Fleetmatics, Verizon Connect is another widely used FMS example. It offers similar features to Fleet Complete, such as real-time vehicle tracking, driver reports, driver behavior monitoring, and fuel management.
- Geotab: Geotab is a telematics platform that includes an FMS for managing vehicle fleets. It offers GPS tracking, vehicle diagnostics, driving data analysis, safety alerts, and regulatory compliance,
- Teletrac Navman: It's a telematics and fleet management solution that provides real-time vehicle tracking, driver performance reports, route planning, and fuel consumption monitoring. It's used in various industries, such as logistics, construction, transportation, and utilities.
- TomTom Telematics: TomTom Telematics offers a fleet management platform that includes vehicle tracking, driver navigation, work order management, driver behavior monitoring, and fleet data analysis. It's used in sectors like transportation, logistics, and field services.

Companies Utilizing Fleet Management Systems (FMS) in Their Operations:

- UPS: The courier and parcel delivery company UPS uses fleet management systems to optimize its delivery routes, manage vehicle maintenance, and monitor driver performance.
- FedEx: Another courier and parcel delivery company, FedEx, also uses fleet management systems to track its vehicles in real-time, optimize deliveries, and improve fleet efficiency.
- DHL: One of the leading logistics companies globally, uses fleet management systems to monitor its vehicles, plan routes, and ensure timely delivery of shipments.
- Amazon: The e-commerce giant uses fleet management systems to manage its extensive delivery vehicle network, ensuring efficient package distribution to customers worldwide.
- Coca-Cola: It uses fleet management systems to optimize the distribution of its products globally, ensuring products reach sales points timely and efficiently.
- Walmart: One of the world's largest retail chains uses fleet management systems to manage its extensive fleet of transport trucks, ensuring efficient goods delivery to its stores.
- Uber Freight: It uses fleet management technology to connect carriers and drivers with available loads, thus optimizing route assignments and cargo management.

These are just some of the many companies using fleet management systems in their operations to improve the efficiency, safety, and productivity of their vehicle fleets.

Implementing mobile applications or online platforms, citizens could receive notifications about recyclable solid waste collection schedules in their areas. This would allow them to prepare and place materials for collection timely, facilitating the process for both parties.

5) Mobile Applications for Drivers and Users

Mobile applications designed specifically for collection vehicle drivers can provide detailed information about assigned routes, scheduled stops, and any real-time changes. This enables drivers to quickly adapt to changing conditions and efficiently follow optimized routes.

One of the proposed solutions to address last-mile logistics challenges in recycling is the implementation of a mobile application with an intuitive and simple interface. This application would allow users to easily locate the nearest recycling points to their location, offering detailed information about the types of materials that can be recycled in each container.

In addition to providing this crucial information, the app would also allow users to request collection services from the comfort of their homes. By simply tapping a few times on their mobile devices, users could schedule the collection of their recyclable materials, thus eliminating the need to physically transport them to recycling points.

This approach has the potential to significantly increase recycling participation by removing access barriers and making the process more convenient for citizens. Furthermore, by enabling collectors to efficiently respond to pickup requests through the app, recycling supply chain management can be improved, ensuring timely collection and reducing the risk of container overflow.

The implementation of a dedicated recycling mobile app with features such as recycling point location and collection request can be an effective strategy to enhance the efficiency and accessibility of last-mile logistics in recycling. Its navigation interface would be as follows

Illustration 7: E-trike Cargo Mockup

SOURCE: Own elaboration (Canva)

Last-mile logistics facilitates the collection and analysis of data on the generation and management of recyclable solid waste in the city. This would help local authorities better understand waste generation patterns and adjust their management strategies accordingly.

By integrating last-mile logistics with the operations of recycling companies and solid waste processing centers, the efficient delivery of collected materials to recycling facilities could be facilitated. This would contribute to closing the recycling loop and promoting a circular economy in Popayán.

6) Application of Last-Mile Logistics in the Downtown Area of Popayán

The downtown area of Popayán, also known as the Historic Center, consists of approximately 67 blocks. This area is of great cultural and architectural importance, as it preserves colonial buildings and significant historical monuments.

The collection of recyclable solid waste in the downtown area of Popayán currently faces significant challenges due to logistical inefficiency and lack of an optimized system. To address these issues, we propose the implementation of a comprehensive solution using electric cargo tricycles equipped with advanced technology.

7) Logistics Optimization Strategy

a) Nearest Neighbor Algorithm (NN)

Using the Nearest Neighbor Algorithm, efficient collection routes can be planned for electric cargo tricycles effectively and accurately. This algorithm systematically selects the next closest stop to the tricycle's current location, significantly reducing both travel time and distance. By always choosing the nearest destination, the Nearest Neighbor Algorithm optimizes collection routes, ensuring that tricycles follow the shortest and most efficient path possible. This route planning strategy is essential for maximizing the operational efficiency of electric cargo tricycles. By minimizing the total distance traveled, operating time is reduced, allowing drivers to complete more routes within a given period. This not only improves the productivity of the collection system but also contributes to faster and more reliable service for users..

Furthermore, reducing distance and travel time has a direct impact on the energy consumption of electric tricycles. A more efficient route means lower energy consumption and, therefore, greater autonomy. This not only extends the life of the batteries but also reduces the frequency of necessary recharges, which can translate into significant savings in operating costs. The implementation of the Nearest Neighbor Algorithm also facilitates real-time adaptation to changes and contingencies. For example, if a specific container needs to be emptied urgently or if a planned route becomes inaccessible due to construction or traffic, the algorithm can quickly recalculate the best alternative route. This flexibility is crucial for maintaining the efficiency and punctuality of the collection service.

The use of this algorithm can be integrated with Geographic Information Systems (GIS) and mobile applications, providing drivers with precise and updated navigation instructions. This not only improves route efficiency but also reduces cognitive load on drivers, allowing them to focus on driving and waste collection..

b) Trash Container Fill Sensors

Installing fill sensors in containers allows real-time monitoring of waste levels, offering an advanced and efficient solution for solid waste management. These sensors, connected to a centralized monitoring network, send automatic alerts when containers reach their maximum capacity, facilitating need-based collection scheduling and preventing garbage overflow. This system ensures that containers do not remain full for long periods, improving both operational efficiency and the quality of the urban environment. Additionally, by avoiding garbage overflow, sanitation and aesthetic conditions in urban areas are significantly improved. Containers that do not overflow help prevent the proliferation of pests and unpleasant odors, contributing to a cleaner and healthier environment for residents and visitors. This is especially important in high-traffic areas such as historic centers and commercial areas, where the presence of uncollected waste can have a negative impact on the city's image and the quality of life of its inhabitants. Fill sensor technology also allows integration with other waste management tools, such as mobile applications and data analysis platforms. Administrators can receive alerts on their mobile devices and access control panels displaying the status of the containers, facilitating quick, data-driven decision-making. This integration improves responsiveness to unforeseen situations, such as a sudden increase in waste generation due to special events or seasonal changes.

c) Trash Container Weight Sensors

Equipping containers with weight sensors allows for determining the exact amount of waste in each container, providing precise and real-time data on the current load. This information is crucial for better managing the load of electric cargo tricycles equipped with solar panels and avoiding overloading, ensuring a balanced distribution of waste and optimizing the efficiency of the collection system. Integrated weight sensors in containers provide several significant advantages. By knowing the exact weight of the waste in each container, operators can plan and distribute the load more evenly among the tricycles, avoiding overloads that could damage the vehicles or reduce their efficiency, and ensuring that each tricycle operates within its optimal limits. Weight information allows for adjusting collection routes in real-time, directing tricycles to the fullest containers first and avoiding unnecessary trips to partially empty containers. This improves route efficiency and reduces energy consumption, especially important for electric tricycles that rely on batteries and solar panels. By avoiding overloading tricycles, vehicle lifespan is extended, and wear on components is minimized.

Trash Sorting Sensors

Implementing sensors that automatically sort recyclable waste significantly improves the efficiency of waste collection and processing. These advanced sensors, capable of identifying and segregating materials such as plastic, glass, paper, and metals from the source, represent a crucial innovation in waste management. Automatic waste sorting through sensors reduces the need for manual separation, which not only speeds up the process but also reduces human errors and improves the quality of recycled material. Sensors can detect different types of materials using technologies such as optical recognition, near-infrared spectroscopy (NIR), and density analysis, ensuring precise and effective separation.

Implementing these sensors from the point of origin, i.e., in the waste containers themselves, allows segregation to begin as soon as the material is deposited. This means that recyclable waste arrives already separated at collection centers, greatly simplifying the subsequent processing process. By reducing cross-contamination between recyclable and non-recyclable materials, recycling quality is improved, and the value of recovered materials is maximized.

d) GPS Tracking Devices on Electric Tricycles

Electric cargo tricycles will be equipped with state-of-the-art GPS devices for real-time tracking and efficient collection route management. This advanced technology allows constant monitoring of the location and movement of each tricycle, giving operators the ability to optimize routes based on traffic conditions and collection needs. Using GPS devices on tricycles offers several key advantages. First, real-time tracking provides waste managers with accurate and updated insight into collection operations at all times. This enables informed decision-making and efficient resource allocation based on the specific needs of each collection area.

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Additionally, the ability to optimize routes on the fly leads to a significant reduction in tricycle downtime. By quickly adapting to unforeseen changes in traffic or environmental conditions, the operational efficiency of the electric tricycle fleet is maximized.

e) Communication and Fleet Management Devices

Integrating communication and fleet management systems represents a significant step in improving efficiency and coordination in waste collection services. These systems allow seamless communication between electric tricycle drivers and the control center, facilitating real-time operation coordination and improving responsiveness to any eventuality. Real-time data transmission through these systems offers several key benefits. Firstly, it allows constant monitoring of the location and status of each tricycle, providing operators with a comprehensive view of ongoing operations.

This facilitates informed decision-making and efficient resource allocation based on the specific needs of each collection area. Additionally, real-time communication between drivers and the control center improves responsiveness to any unforeseen events or changes in operating conditions. Drivers can quickly report any incidents, such as mechanical issues, roadblocks, or changes in the amount of waste to be collected, allowing the control center to take necessary action promptly and effectively.

f) Radio Frequency Identification (RFID) Devices

Implementing Radio Frequency Identification (RFID) technology in containers represents a significant advancement in efficient resource management and waste collection process optimization. RFID devices enable quick and accurate identification of each container, greatly facilitating inventory management and ensuring that each one is emptied and recorded correctly in the system. RFID technology operates by emitting radio signals that are picked up by nearby readers or antennas, allowing for automatic and contactless identification and tracking of containers. This remote and non-line-of-sight identification capability significantly streamlines container collection and registration processes.

By using RFID in containers, several significant advantages are obtained. Firstly, rapid and accurate identification allows collection operators to locate and manage containers efficiently, reducing downtime and improving overall productivity. Additionally, RFID technology facilitates real-time tracking of container location and status, providing waste managers with a comprehensive and updated view of collection operations at all times..

g) Temperature and Humidity Sensors

Temperature and humidity sensors installed in containers play a crucial role in monitoring environmental conditions that may affect the degradation of recyclable waste. These sensors provide real-time data on conditions inside containers, allowing waste managers to take proactive measures to maintain the optimal conditions necessary to preserve the quality of recyclable materials. Maintaining optimal temperature and humidity conditions is essential to prevent premature degradation of recyclable waste. Materials such as paper, cardboard, and certain plastics can deteriorate rapidly if stored under inadequate conditions, thereby losing their value and viability for recycling. For example, excessive humidity can cause paper and cardboard to disintegrate or develop mold, while extreme temperatures can affect the integrity of plastics.

Additionally, constant monitoring of environmental conditions inside containers can help prevent public health problems. The accumulation of waste under unfavorable conditions can generate unpleasant odors and attract disease vectors such as rodents and insects. Temperature and humidity sensors allow detection of these conditions before they become a problem, facilitating timely intervention, such as emptying and cleaning affected containers. Implementing these sensors also provides valuable data for analysis and continuous improvement of waste management processes. Administrators can identify patterns and trends in container environmental conditions, adjusting collection and storage strategies accordingly. This not only improves operational efficiency but also contributes to the sustainability of the waste management system. Integrating these sensors with mobile applications and data management platforms allows managers to receive real-time alerts and notifications about any significant changes in conditions inside containers. This rapid responsiveness is critical for addressing any potential issues before they escalate, ensuring the preservation of recyclable materials and the protection of public health.

h) Mobile Applications for Drivers and Users

Developing mobile applications for both tricycle drivers and collection service users significantly improves communication and process efficiency. These applications allow drivers to receive optimized routes based on current location and traffic, as well as real-time updates on new collection requests, helping them plan their routes more effectively.

Additionally, applications can provide information about the status of containers, notifying drivers when and where additional services are needed. On the other hand, users of collection services also greatly benefit from these applications. They can notify drivers when their containers need to be emptied with just a few clicks on their mobile devices. Additionally, applications can include additional features, such as real-time tracking of tricycle arrival, providing users with greater transparency and predictability of the service. They can also offer automatic reminders to take out containers on scheduled collection days, improving punctuality and organization..

i) Sistemas de Información Geográfica (SIG)

Utilizar Google Maps como plataforma SIG permite una mejor visualización y análisis de las rutas de recolección, ofreciendo múltiples beneficios tanto para la planificación como para la ejecución de los servicios. Google Maps proporciona herramientas accesibles y avanzadas para mapear y analizar datos geográficos, lo que facilita enormemente la planificación y optimización de las rutas de recolección. Con Google Maps, los administradores pueden visualizar de manera clara y detallada las áreas de servicio, identificando las rutas más eficientes y evitando zonas con tráfico pesado o restricciones de acceso. La capacidad de superponer datos geográficos permite una comprensión más profunda de los patrones de recolección, como las áreas con mayor densidad de residuos o las ubicaciones de los contenedores que requieren vaciado con mayor frecuencia.

Additionally, Google Maps allows for the integration of real-time data, which means that routes can be dynamically adjusted in response to traffic conditions or new service requests. This real-time adaptability improves operational efficiency and reduces the time and costs associated with waste collection. Another significant advantage is the ability to share routes and geographic data directly and in real-time with drivers. Drivers can access optimized routes through their mobile devices, receiving precise instructions and instant updates. This not only improves communication between administrators and drivers but also reduces the possibility of errors and increases service punctuality. Google Maps also offers analytical tools that allow administrators to review the performance of collection routes, identify areas for improvement, and adjust strategies as needed. The generated reports can include key metrics such as total collection time, distance traveled, and fuel efficiency, providing a solid basis for informed decision-making.

Expected Benefits

- Operational Efficiency: Combining the Nearest Neighbor Algorithm with real-time tracking significantly reduces travel time and distance, improving operational efficiency.
- Environmental Impact Reduction: The use of electric cargo tricycles reduces carbon emissions and contributes to more sustainable waste collection.
- Improved Working Conditions: The implemented technology reduces the workload and risks associated with waste collection, improving working conditions for collectors.
- Increased Recycling Rate: Efficient waste segregation at the source and timely collection increase the amount of recyclable materials recovered.

If support is obtained from both public and private institutions, the steps to implement last-mile logistics in the collection of recyclable solid waste in Popayán would be as follows:

- Initial Evaluation: Map the 67 blocks of downtown Popayán to identify critical points and optimal locations for sensors and containers.
- Technology Deployment: Install sensors and devices on containers and electric tricycles.
- Staff Training: Train drivers and operators in using the new technologies and mobile applications.
- Continuous Monitoring: Implement a real-time monitoring system to adjust routes and operations based on collected data.
- Evaluation and Improvement: Conduct periodic evaluations of the system to identify areas for improvement and continuously optimize collection operations.

With this comprehensive approach, Popayán can significantly improve the logistics of recyclable solid waste collection, contributing to a cleaner and more sustainable urban environment.

III. ANALYSIS OF RESULTS

1) Viability of the Electric Cargo Tricycle: The results show that implementing an electric cargo tricycle is feasible for improving solid waste management in Popayán. This is due to its ability to efficiently transport heavy loads and its potential to reduce the environmental impact of waste collection.
2) Environmental Impact: The introduction of the electric cargo tricycle is observed to help reduce the environmental impact generated by the accumulation of unrecycled waste. By facilitating more efficient and sustainable collection, it is expected to decrease the amount of waste ending up in landfills, thus contributing to environmental preservation.
3) Improvements in Working Conditions: The results also suggest that using the electric cargo tricycle can improve the working conditions of solid waste collectors. By providing a more suitable and efficient means of transportation, it would reduce the workload and minimize occupational health risks associated with heavy lifting and long distances.
4) Need for Investments and Institutional Support: Although the feasibility of the electric cargo tricycle is demonstrated, the analysis also highlights the need for investments and institutional support for its successful implementation. This includes the acquisition of equipment, staff training, charging infrastructure, and appropriate regulations for its operation in the urban environment.
5) The project results suggest that introducing an electric cargo tricycle for solid waste collection in Popayán can offer significant benefits in terms of operational efficiency, environmental impact, and working conditions. However, an integrated approach involving both local authorities and relevant stakeholders is required to ensure its long-term success.

IV. CONCLUSIONS

1) The study confirms that the implementation of an electric cargo tricycle can significantly improve efficiency in solid waste management in Popayán. This vehicle allows for more agile and effective transport of heavy loads, proving to be a practical and economical solution for waste collection. The tricycle's ability to maneuver in tight spaces and its lower maintenance needs compared to traditional vehicles make this option particularly viable for Popayán's urban infrastructure.
2) The introduction of the electric cargo tricycle presents significant environmental advantages. By facilitating more efficient and sustainable collection, this vehicle helps reduce the amount of unused waste ending up in landfills, thus contributing to a decrease in soil and water pollution. Additionally, being an electric vehicle, it reduces greenhouse gas emissions and noise pollution, promoting a cleaner and healthier environment. This approach not only supports efforts towards a circular economy in the city but also aligns with global sustainability and climate change mitigation goals.
3) The study's results indicate that the electric cargo tricycle can significantly alleviate the working conditions of solid waste collectors. By providing a more suitable and ergonomic means of transportation, physical efforts and health issues related to manual transportation of heavy loads and long distances on foot can be minimized. This not only improves the quality of life for collectors but can also increase their productivity and reduce absenteeism due to health issues. Additionally, the ease of use of the tricycle can encourage greater professionalization and stability in this job sector.
4) Although the electric cargo tricycle proves to be a viable and beneficial solution, the study highlights the need to overcome several challenges for its successful implementation. These challenges include the need for significant investments in acquiring tricycles and necessary charging infrastructure. Adequate training of personnel for handling and maintaining the vehicles is also required. Furthermore, it is essential to develop specific regulations that facilitate the operation of electric tricycles in Popayán's urban areas, ensuring safety and efficiency in their use. Cooperation between local authorities, private companies, and the community is crucial to effectively address these challenges.
5) The project suggests that to achieve effective implementation of the electric cargo tricycle, it is crucial to have a comprehensive strategic plan involving all stakeholders. Development of supportive policies by the local government, including tax incentives and grants for the purchase of electric tricycles, is recommended. Additionally, financing programs and microcredits can facilitate the adoption of this technology by collectors. Awareness and education campaigns are vital to promoting acceptance and proper use of the tricycles. Establishing public-private partnerships to share costs and benefits is also recommended, ensuring a collaborative and sustainable approach.
6) The adoption of an electric cargo tricycle in solid waste collection in Popayán has the potential to bring significant improvements in terms of operational efficiency, reduction of environmental impact, and enhancement of collectors' working conditions.

However, to ensure its sustainability and long-term success, a coordinated approach backed by adequate investments and institutional support is required. Collaboration between local authorities, the community, and the private sector will be essential to overcome challenges and maximize the benefits of this innovative waste collection solution.

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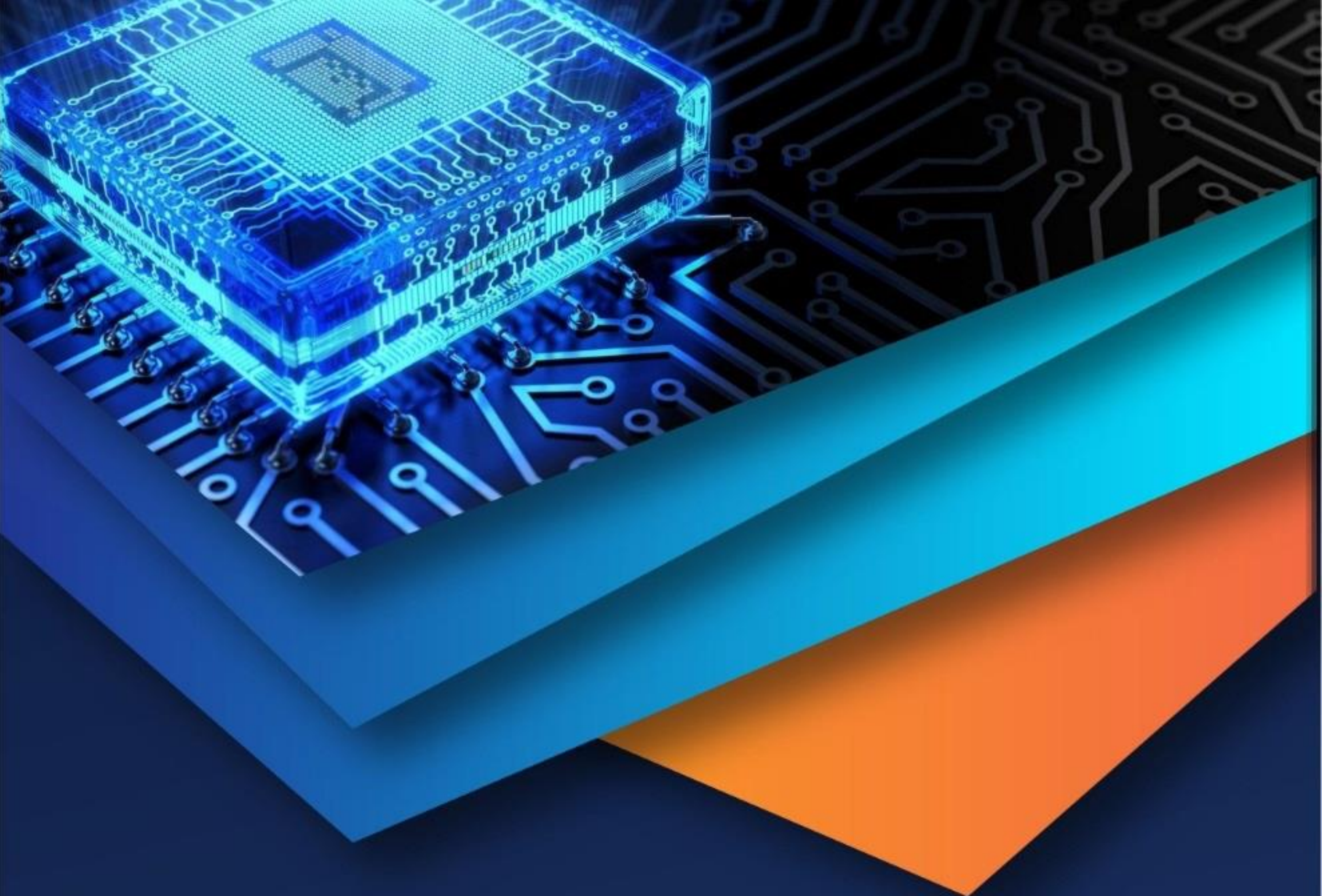

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