

Cycling infrastructure and sustainable mobility in intermediate cities: technical and functional evaluation of an alternative for an urban corridor

Infraestructura ciclista y movilidad sostenible en ciudades intermedias: evaluación técnica y funcional de una alternativa en un corredor urbano

Infraestrutura ciclovária e mobilidade sustentável em cidades intermediárias: avaliação técnica e funcional de uma alternativa para um corredor urbano

Yeny Natalia Mancipe Cristiano¹
Valery Wolf Lara²
Ana María Mejía Peña³

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¹ Researcher, Division of Architecture and Engineering, Universidad Santo Tomás, Villavicencio Branch, Campus Aguas Claras, Villavicencio, Colombia.

Email: yenymancipe@ustavillavicencio.edu.co

ORCID: <https://orcid.org/0000-0003-3950-7098>

CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0001689465

² Researcher, Civil Engineering Program, Faculty of Civil Engineering, Universidad Santo Tomás, Villavicencio Branch, Campus Aguas Claras, Villavicencio, Colombia.

Email: valerywolf@ustavillavo.edu.co

ORCID: <https://orcid.org/0009-0009-8160-428X>

CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0002491699

³ Researcher, Civil Engineering Program, Faculty of Civil Engineering, Universidad Santo Tomás, Villavicencio Branch, Campus Aguas Claras, Villavicencio, Colombia.

Email: anamejia@ustavillavo.edu.co

ORCID: <https://orcid.org/0009-0001-8810-2073>

CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?cod_rh=0002494835



Abstract

Introduction: This article is the result of the research project "Cycling Infrastructure and Sustainable Mobility in Intermediate Cities: Technical and Functional Evaluation of an Alternative for an Urban Corridor", conducted at Universidad Santo Tomás in 2026, aimed at evaluating the implementation of bidirectional cycling infrastructure within an urban corridor in Villavicencio, Colombia.

Problem: The corridor currently lacks adequate cycling and pedestrian infrastructure, generating conflicts between motorized and non-motorized users and reducing safety and accessibility.

Objective: The objective of this research is to evaluate the technical and functional feasibility of implementing a bidirectional sidewalk bicycle lane within the study corridor.

Methodology: The study integrated vehicular, pedestrian, and cyclist traffic counts, roadway inspections, citizen perception surveys, street plans, and mobility simulations using PTV Vissim to compare current and proposed operational scenarios.

Results: The analyses identified favorable territorial and operational conditions for implementing cycling infrastructure. Ninety-six percent of respondents supported the implementation of a bidirectional bicycle lane, 81% expressed willingness to use it, and 94% considered the corridor unsafe for pedestrians and cyclists. PTV Vissim simulations reported an average operating speed of 19.23 km/h, an average delay of 36.11 s, and bicycle lane occupancy rates ranging from 1.05% to 1.14%.

Conclusion: The proposed bidirectional bicycle lane represents a technically viable alternative for improving active mobility along the study corridor while maintaining stable operational conditions and supporting the sustainable mobility objectives established for the city.

Originality: The study integrates roadway diagnosis, citizen perception, and traffic simulation to evaluate cycling infrastructure in Villavicencio.

Limitations: The research was constrained by geometric restrictions and limited roadway information in certain sections of the corridor.

Keywords: Traffic simulation; public perception; two-way bike path; mid-sized city.

Resumen

Introducción: Este artículo es el resultado del proyecto de investigación "Infraestructura ciclista y movilidad sostenible en ciudades intermedias: evaluación técnica y funcional de una alternativa en un corredor urbano", desarrollado en la Universidad Santo Tomás durante el año 2026, orientado a evaluar la implementación de infraestructura ciclista bidireccional dentro de un corredor urbano en Villavicencio, Colombia.

Problema: El corredor actualmente carece de infraestructura adecuada para ciclistas y peatones, generando conflictos entre usuarios motorizados y no motorizados y reduciendo las condiciones de seguridad y accesibilidad.

Objetivo: El objetivo de la investigación es evaluar la factibilidad técnica y funcional de implementar una ciclorruta bidireccional sobre la acera dentro del corredor de estudio.

Metodología: El estudio integró aforos vehiculares, peatonales y ciclistas, inspecciones viales, encuestas de percepción ciudadana, elaboración de planos y simulaciones de movilidad mediante PTV Vissim para comparar escenarios operacionales actuales y propuestos.

Resultados: Los análisis identificaron condiciones territoriales y operacionales favorables para la implementación de infraestructura ciclista. El 96% de los encuestados respaldó la implementación de una ciclorruta bidireccional, el 81% manifestó disposición a utilizarla y el 94% consideró inseguro el corredor para peatones y

ciclistas. La simulación en PTV Vissim registró una velocidad promedio de operación de 19.23 km/h, un retraso promedio de 36.11 s y una tasa de ocupación de la ciclorruta entre 1.05% y 1.14%.

Conclusión: La implementación de una ciclorruta bidireccional representa una alternativa técnicamente viable para mejorar la movilidad activa del corredor, manteniendo condiciones operacionales estables e integrándose a las estrategias de movilidad sostenible establecidas para la ciudad.

Originalidad: El estudio integra diagnóstico vial, percepción ciudadana y simulación de tráfico para evaluar la infraestructura ciclista en Villavicencio.

Limitaciones: La investigación estuvo condicionada por restricciones geométricas y por información vial limitada en algunos tramos del corredor.

Palabras clave: Simulación de tráfico; percepción ciudadana; ciclorruta bidireccional; ciudad intermedia.

Resumo

Introdução: Este artigo é resultado do projeto de pesquisa "Infraestrutura cicloviária e mobilidade sustentável em cidades intermediárias: avaliação técnica e funcional de uma alternativa para um corredor urbano", desenvolvido na Universidad Santo Tomás em 2026, com o objetivo de avaliar a implementação de infraestrutura cicloviária bidireccional em um corredor urbano de Villavicencio, Colômbia.

Problema: O corredor atualmente não dispõe de infraestrutura adequada para ciclistas e pedestres, gerando conflitos entre usuários motorizados e não motorizados e reduzindo as condições de segurança e acessibilidade.

Objetivo: Avaliar a viabilidade técnica e funcional da implementação de uma ciclovia bidireccional sobre a calçada no corredor estudado.

Metodologia: O estudo integrou contagens de tráfego veicular, pedonal e cicloviário, inspeções viárias, pesquisas de percepção cidadã, elaboração de planos e simulações de mobilidade utilizando PTV Vissim para comparar os cenários operacionais atuais e propostos.

Resultados: As análises identificaram condições territoriais e operacionais favoráveis à implementação da infraestrutura cicloviária. Noventa e seis por cento dos entrevistados apoiaram a implementação de uma ciclovia bidireccional, 81% manifestaram disposição para utilizá-la e 94% consideraram o corredor inseguro para pedestres e ciclistas. As simulações no PTV Vissim registraram velocidade média de operação de 19,23 km/h, atraso médio de 36,11 s e taxas de ocupação da ciclovia entre 1,05% e 1,14%.

Conclusão: A ciclovia bidireccional proposta representa uma alternativa tecnicamente viável para melhorar a mobilidade ativa no corredor, mantendo condições operacionais estáveis e contribuindo para os objetivos de mobilidade sustentável da cidade.

Originalidade: O estudo integra diagnóstico viário, percepção cidadã e simulação de tráfego para avaliar a infraestrutura cicloviária em Villavicencio.

Limitações: A pesquisa foi condicionada por restrições geométricas e pela disponibilidade limitada de informações viárias em alguns trechos do corredor.

Palavras-chave: Simulação de tráfego; percepção pública; ciclovia bidireccional; cidade de médio porte.

1. INTRODUCTION

In recent decades, urban mobility has undergone significant transformations associated with accelerated urban growth, the expansion of metropolitan areas, and the continuous increase in motor vehicle ownership. According to the United Nations, approximately 68% of the world's population is expected to live in urban areas by 2050, intensifying the pressure on transportation systems and urban infrastructure [1]. This scenario has generated problems related to traffic congestion, environmental deterioration, road safety, and reduced accessibility, particularly in intermediate cities where transport planning has not always evolved at the same pace as territorial expansion. In response to these challenges, sustainable mobility has emerged as a fundamental approach for promoting safer, more efficient, and environmentally responsible transportation systems, encouraging the use of non-motorized modes of transport such as bicycles [2].

In the case of Villavicencio, urban growth and the consolidation of residential, commercial, and educational sectors have increased daily mobility demands and intensified pressure on the existing road infrastructure. The corridor connecting Universidad Santo Tomás with the Hacaritama and La Alborada neighborhoods constitutes one of the city's main access routes to Puerto López and presents constant interaction among pedestrians, cyclists, public transportation, and private vehicles. However, the current road conditions do not provide adequate infrastructure for safe bicycle circulation, generating conflicts among transportation modes and increasing road safety risks for vulnerable users.

From a regulatory perspective, the *Plan de Ordenamiento Territorial* (Land Use Plan, POT) establishes the need to strengthen sustainable mobility strategies and integrate non-motorized transportation modes into the urban transport system [10]. Similarly, the *Guía de Cicloinfraestructura para Ciudades Colombianas* (Cycling Infrastructure Guide for Colombian Cities) recommends the implementation of segregated and continuous bicycle corridors in urban areas with high mobility demand, emphasizing the importance of safety, accessibility, and connectivity criteria in the design process [12]. These guidelines support the technical and territorial relevance of evaluating cycling infrastructure alternatives within the study corridor.

Although several studies have addressed cycling infrastructure design and sustainable mobility strategies, many investigations focus primarily on geometric or operational aspects without integrating technical, territorial, and functional evaluations within a specific urban context. Therefore, there is a need for research capable of combining roadway diagnostics, territorial analysis, citizen perception, and mobility

simulation to support decision-making processes related to sustainable urban mobility interventions in intermediate cities.

Therefore, the general purpose of this research is to technically and functionally evaluate the implementation of a two-way bike path along the corridor connecting Universidad Santo Tomás with the Hacaritama and La Alborada neighborhoods in Villavicencio. The specific objectives are:

1. To diagnose the current mobility conditions of the study corridor to characterize its operational performance and road safety conditions.
2. To analyze the current regulatory and planning framework applicable to the corridor in order to establish technical guidelines for project development.
3. To formulate two bicycle lane alternatives for the study corridor and evaluate their technical feasibility.
4. To assess the impacts of the proposed alternatives on mobility, road safety, and corridor functionality through the modeling of current and projected traffic scenarios, thereby providing technical support for selecting the most viable alternative and supporting future urban mobility decision-making processes.

1.1 Research Background

1.1.1 Sustainable Mobility and Cycling Infrastructure

The bicycle has progressively gained relevance as a viable alternative for daily urban trips due to its environmental, economic, and social benefits. Heinen, van Wee, and Maat [3] state that the implementation of adequate cycling infrastructure directly influences the increase in bicycle commuting, especially for short- and medium-distance urban trips. International experiences have demonstrated that investment in cycling infrastructure can significantly transform mobility dynamics within cities. In the Netherlands, cycling represents nearly 27% of all urban trips, supported by an extensive network of segregated bicycle lanes and integrated transport policies [4]. Likewise, Copenhagen has consolidated one of the most efficient cycling systems worldwide, where approximately 62% of residents commute daily by bicycle due to the availability of safe and connected infrastructure [5]. Similarly, Asian cities have incorporated innovative cycling solutions as part of their urban mobility strategies. In 2017, the city of Xiamen, China, inaugurated the world's longest elevated bicycle lane, extending approximately 8 km, with the purpose of reducing traffic congestion and

promoting sustainable transportation alternatives [6]. These international experiences demonstrate that cycling infrastructure not only contributes to reducing vehicular dependence but also improves accessibility, promotes healthier lifestyles, and enhances the operational functionality of urban corridors.

1.1.2 Cycling Infrastructure in Latin America and Colombia

In Latin America, several cities have advanced in the implementation of cycling infrastructure as part of sustainable mobility policies. Vasallo and Bueno [7] highlight that cities such as Bogotá, Medellín, São Paulo, and Santiago have strengthened their cycling networks in recent years in response to increasing traffic congestion and environmental concerns. Bogotá has developed one of the largest bicycle lane systems in the region, currently exceeding 600 km of cycling infrastructure [8]. During the COVID-19 pandemic, the city also experienced a significant increase in bicycle use, consolidating cycling as an efficient and resilient mode of transportation [9].

Nevertheless, despite these advances, many Colombian and Latin American intermediate cities still present deficiencies regarding the continuity, connectivity, and safety of their cycling networks, limiting the consolidation of bicycles as a reliable transportation alternative. In Colombia, studies conducted by [13] and [14] emphasize the importance of evaluating current road conditions, citizen perception, and infrastructure feasibility to ensure the successful implementation of sustainable mobility projects. These investigations highlight the need to integrate technical, social, and territorial analyses during the planning process for urban cycling infrastructure, particularly in cities where active mobility systems remain underdeveloped.

2. MATERIALS AND METHODS

The present research was developed as an applied study focused on the technical and functional evaluation of the implementation of a bidirectional bicycle lane along an urban corridor in the city of Villavicencio. A mixed-methods approach was adopted, integrating both quantitative and qualitative analysis tools, thereby allowing the evaluation of the physical conditions of the corridor as well as users' perceptions of mobility within the sector, in accordance with contemporary sustainable transportation planning approaches.

The methodological process was structured progressively, beginning with the characterization of the current conditions of the corridor to identify its operational, geometric, and functional characteristics. Subsequently, a citizen perception analysis

was conducted, together with the consolidation of the baseline information required for the formulation of design alternatives and the evaluation of future mobility scenarios. This comprehensive approach has been widely applied in urban mobility studies because it enables the integration of technical analysis with the actual territorial dynamics and mobility needs of the population [2], [13].

2.1 Diagnostic Phase

A diagnostic phase was conducted within the study corridor connecting Universidad Santo Tomás with the Hacaritama and La Alborada neighborhoods to identify the current mobility conditions and operational characteristics of the sector. For this purpose, vehicular, pedestrian, and bicycle traffic counts were carried out at different strategic points along the corridor to determine traffic volumes, predominant travel patterns, and the interaction among the various road users. These measurements constitute a fundamental tool for understanding urban traffic behavior and mobility dynamics, providing a quantitative basis for subsequent modeling and technical evaluation processes [2].

Considering the educational, commercial, and service-related nature of the corridor, traffic counts were conducted between 12:00 p.m. and 2:00 p.m., corresponding to the period with the greatest interaction among students, pedestrians, cyclists, public transport users, motorcyclists, and private vehicle users associated with midday activities and class changes. Although Villavicencio presents additional periods of high vehicular demand, these intervals are affected by traffic restriction measures such as the *Pico y Placa* program (license plate-based vehicle restriction program), implemented between 6:30–9:30 a.m. and 5:00–8:00 p.m. for private vehicles, limiting the observation of simultaneous interactions among transport modes under unrestricted operational conditions [16]. Therefore, the selected period allowed the characterization of representative multimodal operational conditions within the corridor, in accordance with the objectives of the study.

The traffic volumes recorded in both directions of the corridor during the selected traffic count period are presented in Tables 1 and 2, corresponding to the Universidad Santo Tomás–Hacaritama direction and the La Alborada–Universidad Santo Tomás direction, respectively.

Table 1. Traffic volumes in the Universidad Santo Tomás-Hacaritama direction.

Vehicle Type	Bicycles	Pedestrians	Cars	Bus	Truck	Motorcycles
Amount	69	57	2321	106	82	2290

Source: own work

Table 2. Traffic volumes in the La Alborada-Universidad Santo Tomás direction.

Vehicle Type	Bicycles	Pedestrians	Cars	Bus	Truck	Motorcycles
Amount	39	35	2006	138	110	2073

Source: own work

Additionally, a geometric and physical assessment of the corridor was performed, considering variables such as roadway width, sidewalk conditions, longitudinal slopes, pavement condition, drainage characteristics, and the identification of critical points associated with mobility conflicts. The evaluation of these parameters is essential in cycling infrastructure planning processes, since they directly influence user safety, travel comfort, and route continuity [10], [12]. Simultaneously, a social analysis component was incorporated through the implementation of a digital survey addressed to pedestrians, cyclists, drivers, and frequent corridor users. The questionnaire was distributed through an online form (<https://forms.gle/2N5jL75ThrUK-J64aA>), obtaining a total of 362 respondents. Considering a target population of 5,044 members belonging to the Universidad Santo Tomás community, the representative sample size was calculated using the finite population formula with a 95% confidence level and a 5% margin of error, resulting in an estimated sample of approximately 357 surveys, therefore, the sample collected adequately represents the target population. The general distribution of the sample is presented in Table 3.

Table 3. Distribution of the surveyed sample.

User Profile	Percentage	Number of Respondents
Pedestrians	25%	91
Cyclists	35%	127
Drivers	22%	80
Frequent Corridor Users	18%	64
Total	100%	362

Source: own work

The structured questionnaire consisted of dichotomous and multiple-choice questions aimed at identifying users' perceptions of the current mobility conditions of the corridor, particularly the limitations generated by the absence of adequate cycling infrastructure, as well as their willingness to use a potential bidirectional bicycle lane. The incorporation of citizen perception instruments complements the technical analysis with relevant social information, considering that the lack of safe and continuous infrastructure is one of the principal factors limiting the adoption of non-motorized modes of transport and the daily use of bicycles as an urban mobility alternative [13], [19].

To evaluate the internal consistency of the responses obtained from the dichotomous questions, the Kuder–Richardson 20 (KR-20) reliability method was applied, obtaining a coefficient of 0.82. This result indicates an adequate level of internal consistency and acceptable reliability of the instrument implemented for the subsequent analysis of the collected data.

2.2 Technical and Functional Study

The technical and functional study constitutes a fundamental stage in the planning of sustainable mobility projects because it allows the evaluation of the technical, operational, territorial, and functional conditions required for the implementation of roadway interventions. According to the *Guía de Cicloinfraestructura para Ciudades Colombianas* [12], the evaluation of cycling infrastructure must consider criteria related to road safety, accessibility, urban integration, and compatibility with existing mobility dynamics, in addition to the geometric characteristics of the corridor. Likewise, contemporary approaches to sustainable transportation planning emphasize the need to develop infrastructure capable of responding to actual mobility demands and improving travel conditions for vulnerable road users [2].

In Villavicencio, expansive and low-density urban growth has increased mobility demands and pressure on urban infrastructure. Studies on the city's territorial planning indicate that the 2015 *Plan de Ordenamiento Territorial de Villavicencio* increased urban and expansion land by 43.3% compared with the previous POT, favoring expansion toward peripheral sectors [17]. Among these strategic corridors is the segment connecting Universidad Santo Tomás with the Hacaritama and La Alborada neighborhoods, located along Carrera 22 toward the Puerto López corridor. This sector concentrates trips associated with academic, residential, commercial, and service activities, generating constant interaction among pedestrians, cyclists, motorcyclists, public transport users, and private vehicle users. According to the United Nations,

intermediate cities have experienced significant increases in urban mobility demand due to urban and demographic growth [1].

From a territorial perspective, the proposal is aligned with the *Plan de Ordenamiento Territorial de Villavicencio*, which promotes sustainable mobility and active transportation systems [10]. The existing and projected cycling network defined in the POT demonstrates the strategic importance of strengthening non-motorized connectivity among different urban sectors, as shown in Figure 1. The analyzed corridor is classified as a V2 roadway corridor, which includes bidirectional cycling infrastructure and its integration with the *Sistema Estratégico de Transporte Público* (Strategic Public Transport System, SETP). Additionally, the study area is associated with the Strategic Urban Operation “La Alborada,” focused on improving pedestrian connectivity and consolidating non-motorized transportation systems within the sector [10]. The territorial relationship between the corridor and this strategic operation is presented in Figure 2.

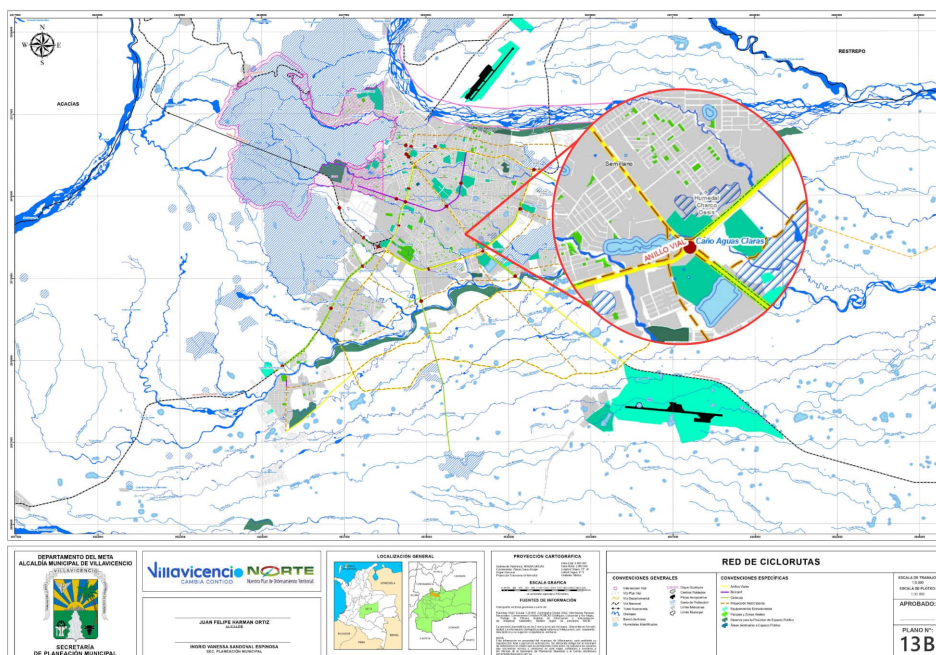


Figure 1. Existing and projected cycling network

Source: Adapted from POT Villavicencio [10].

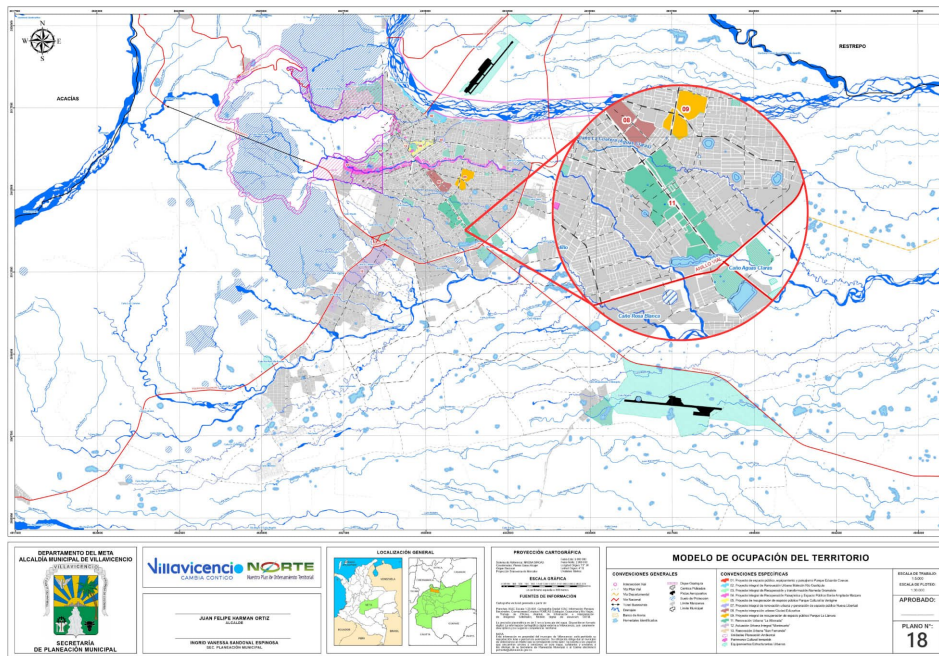


Figure 2. Land occupation model and relationship between the study corridor and the Strategic Urban Operation “La Alborada.”

Source: Adapted from POT Villavicencio [10].

The *Guía de Cicloinfraestructura para Ciudades Colombianas* establishes that cycling corridor planning must prioritize continuity, safety, accessibility, and integration with surrounding urban dynamics. These criteria are commonly considered core indicators of bicycle level of service and bikeability assessments [12], [25]. In this regard, the corridor presents favorable characteristics for the implementation of active mobility infrastructure, including longitudinal continuity, moderate topography, connections with residential and institutional sectors, and proximity to educational facilities that generate short-distance trips. Previous studies indicate that short- and medium-distance urban trips are particularly suitable for bicycle use when adequate infrastructure conditions are provided [3].

From a geometric and territorial perspective, the corridor presents differentiated conditions depending on the traffic direction. In the Universidad Santo Tomás–Hacaritama direction, relatively favorable roadway widths were identified for the incorporation of a bidirectional bicycle lane, although localized restrictions caused by commercial activities and elements partially encroaching on public space were observed. These conditions do not significantly compromise the proposed intervention and allow greater adaptability for roadway redistribution processes. Conversely, the La Alborada–Universidad Santo Tomás segment presents greater physical

restrictions due to reduced roadway width, irregular occupation of public space, and the presence of buildings located close to the roadway edge. In several segments, the existing cross-sectional configuration limits the immediate incorporation of cycling infrastructure without affecting adjacent properties or roadway operations. Therefore, the implementation of a bidirectional bicycle lane would require complementary interventions such as land acquisition, localized demolitions, and geometric adaptations. These conditions demonstrate that, although the corridor is technically viable for cycling infrastructure implementation, the territorial and operational complexity varies throughout the sector.

Preliminary inspections and field analyses indicated that the corridor presents favorable geometric and operational conditions for the development of cycling infrastructure alternatives. The predominantly regular topography facilitates bicycle circulation without requiring significant geometric interventions, while the current roadway widths allow the evaluation of different roadway redistribution strategies. Furthermore, the corridor functions as an important urban connector within the city, favoring its integration into a future active mobility network.

Operationally, the corridor presents mixed traffic dynamics characterized by a high degree of coexistence among motorized and non-motorized users under conditions of limited roadway organization. During peak periods, the absence of exclusive cycling infrastructure generates conflicts among bicycles, motorcycles, pedestrians, and private vehicles, especially near intersections, commercial accesses, and public transportation stops. These conditions negatively affect road safety and reduce vulnerable users' perception of safety. According to [3], perceived safety constitutes one of the most influential factors affecting bicycle use in urban environments.

To evaluate corridor functionality, vehicular, pedestrian, and bicycle traffic counts were conducted during representative operational periods, allowing the identification of traffic composition, circulation patterns, and roadway occupancy levels. Likewise, field observations were carried out to identify critical conflict points, pedestrian discontinuities, informal parking areas, and significant modal interactions. This information constituted the technical basis for the formulation of alternatives and the subsequent mobility simulation process developed using specialized traffic modeling tools [22].

Additionally, 362 surveys were administered to pedestrians, cyclists, students, and frequent corridor users to identify perceptions related to mobility, road safety, and willingness to use cycling infrastructure. The results showed that a considerable proportion of users perceived the corridor as unsafe due to the absence of exclusive infrastructure and conflicts with motorized traffic. Likewise, a high percentage

expressed support for the implementation of a bidirectional bicycle lane as a strategy to improve mobility, accessibility, and road safety conditions within the sector.

Finally, the evaluation incorporated mobility simulation tools through PTV Vissim to analyze the potential operational changes associated with the proposed interventions. According to [2], sustainable mobility planning requires predictive tools capable of evaluating future scenarios and their impact on operational performance, safety, and accessibility. In this regard, the simulations allowed the comparison of current and projected corridor scenarios, evaluating indicators associated with operational functionality, vehicular interaction, and modal coexistence [20].

2.3 Design Requirements

The corridor design is based on the provisions established in Section 2.4 of the *Guía de Cicloinfraestructura para Ciudades Colombianas* [12], which addresses design considerations, infrastructure alternatives, signage systems, and all aspects related to the implementation of cycling infrastructure. According to the design criteria established in this guide, the design considerations adopted for the proposed intervention are presented in Table 4.

Table 4. Profiles of user groups and travel modalities.

Type of Cyclist	Main Travel Purpose	Typical Trip Length	Travel Mode	Average Travel Speed
Daily urban cyclist	Work, school, shopping, personal activities, etc.	3–8 km per trip	Individual trips	15–20 km/h
Urban cargo cyclist	Cargo bicycle used as a work vehicle	3–8 km	Trips with cargo transport as the main purpose	10 km/h
Recreational cyclist	Healthy physical activity	5–12 km	Trips in pairs or small groups	10–15 km/h
Holiday recreational cyclist	Access and enjoyment of nature and rural environments	20–40 km	Family trips or small groups	10–15 km/h
Bicycle tourist	Backpacking tourism, nature, and cultural heritage enjoyment	40–80 km	Individual trips, pairs, or small groups	15–25 km/h
Road/sport cyclist	Intense outdoor physical exercise	50–120 km	Individual trips, small groups, or pelotons	30–35 km/h
Mountain sport cyclist	Intense outdoor exercise in natural environments	30–50 km	Trips mainly in small group	Highly variable depending on terrain slope

Source: Adapted from the *Guía de Cicloinfraestructura para Ciudades Colombianas* [12]

For the functional classification and distribution of the roadways within the study corridor, the specifications established in the *Plan de Ordenamiento Territorial* (POT) of Villavicencio were adopted, as this instrument defines the roadway hierarchy and the integration guidelines for sustainable mobility systems within the city's urban structure [10]. In this context, the proposed intervention focuses on the implementation of a bidirectional sidewalk bicycle lane developed under criteria of connectivity, accessibility, and road safety, seeking to respond to both current mobility dynamics and the urban projections established for the sector.

The adequate integration of the different cycling infrastructure components within the urban roadway network guarantees conditions of safety, continuity, comfort, and operational functionality for bicycle users. According to the *Guía de Cicloinfraestructura para Ciudades Colombianas* issued by the Colombian Ministry of Transport [12], the design of cycling corridors must prioritize the integration of all mobility users by ensuring direct, visible, and coherent routes according to the operational characteristics of the roadway. Likewise, the design process must consider variables such as vehicular flow, operating speed, pedestrian demand, land use, and the potential demand for bicycle trips, avoiding interventions based exclusively on spatial availability.

Within the analyzed corridor, the geometric and urban conditions present differentiated characteristics depending on the traffic direction. In the section located between Universidad Santo Tomás and the Hacaritama sector, greater spatial availability was identified for the incorporation of the bidirectional sidewalk bicycle lane due to the width of the existing roadway profile and the presence of usable lateral spaces. However, field inspections revealed several issues associated with the irregular occupation of public space and built structures that partially reduce the effective width available for the intervention. Conversely, in the direction between La Alborada and Universidad Santo Tomás, implementation conditions become more restrictive because of reduced pedestrian space, public space encroachments, and sections where land acquisition or partial demolition of existing structures would be required to guarantee an adequate cross-sectional configuration for the coexistence of pedestrians and cyclists. These conditions were considered during the technical and functional assessment of the proposed alternatives.

Similarly, the operating speed of motorized vehicles constitutes a determining factor within the design criteria for cycling infrastructure, particularly in corridors characterized by high modal interaction [12]. Although the corridor generally operates

under congested urban traffic conditions and moderate operating speeds, several critical conflict points associated with turning maneuvers, commercial accesses, and vehicle merging movements were identified, especially in the Universidad Santo Tomás–Hacaritama direction, where a high-demand turning movement toward the residential sector is located. Consequently, the proposed design incorporates criteria for physical segregation and spatial redistribution aimed at reducing conflicts among pedestrians, cyclists, and motorized users while guaranteeing adequate operational and safety conditions for all road users.

In accordance with the principles of complete streets and sustainable mobility, the proposal considers the implementation of a segregated bidirectional bicycle lane located on the sidewalk, strategically positioned within the urban profile to maximize visibility at intersections and minimize conflict points associated with vehicular accesses, commercial areas, and informal parking zones. The proposal also incorporates horizontal and vertical signage, safety treatments at crossings, and geometric adaptations intended to preserve route continuity and pedestrian accessibility throughout the corridor. Furthermore, the geometric design of the proposal was supported by the information obtained through topographic surveys, traffic analyses, and the review of urban plans and roadway profiles within the study corridor. These technical inputs allowed the identification of critical sections, interference points, and operational conditions required for the development of functional spatial redistribution alternatives.

3. RESULTS

3.1 Study Area Delimitation

The study area corresponds to the roadway corridor located along Carrera 22 toward the Puerto López corridor, specifically within the section connecting Universidad Santo Tomás with the Hacaritama and La Alborada neighborhoods in the city of Villavicencio. This corridor represents an important urban axis within the city's mobility structure due to the presence of educational, commercial, and service-related activities that generate constant travel flows throughout the day. Likewise, the sector is included within the mobility and urban connectivity strategies established by the *Plan de Ordenamiento Territorial* of Villavicencio [10].

The corridor is composed of two principal traffic directions. In the Universidad Santo Tomás–Hacaritama direction, corresponding to an approximate length of 306.73 m, several land uses associated mainly with institutional and commercial activities were identified, including Universidad Santo Tomás, an automotive window tinting establishment, a residential property, a parcel service center, two bars, and an agricultural machinery dealership. On the other hand, the La Alborada–Universidad Santo Tomás direction, with an approximate length of 420.94 m, includes an automotive dealership, a large vacant lot with abandoned infrastructure, a bar, a restaurant, and the pedestrian bridge providing access to the university.

According to the *Guía de Cicloinfraestructura para Ciudades Colombianas* [12], the delimitation of corridors intended for cycling infrastructure must consider factors related to urban connectivity, modal interaction, trip generation, and integration with strategic urban facilities. In this regard, the analyzed corridor presents significant mobility dynamics due to the constant coexistence among pedestrians, cyclists, motorcyclists, public transport users, and private vehicle users, particularly during periods associated with academic and commercial activities. In addition, the study area is characterized by the presence of educational facilities, commercial establishments, and service areas that generate short- and medium-distance trips, conditions that favor the potential implementation of non-motorized modes of transport within the sector [3]. Similarly, the corridor presents multiple roadway interaction points associated with commercial accesses, turning movements, and pedestrian crossings, aspects that were considered in the technical and functional analysis conducted for the formulation of the proposed bidirectional sidewalk bicycle lane.

3.2 Demand Estimation

The survey consisted of five specific questions administered to the 362 participants comprising the study sample, including members of Universidad Santo Tomás, drivers of motorized and electric vehicles, commercial establishment owners, pedestrians, and cyclists. The following questions were included in the survey instrument:

- How frequently do you travel through this corridor? (See Figure 3)

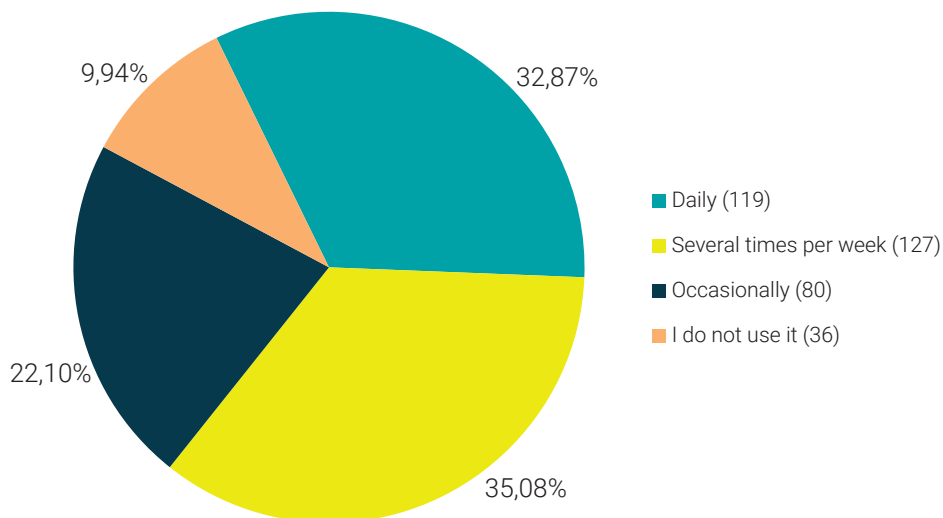


Figure 3. Results obtained for the first survey question.

Source: own work

- Do you consider the corridor safe for pedestrians and cyclists? (See Figure 4)

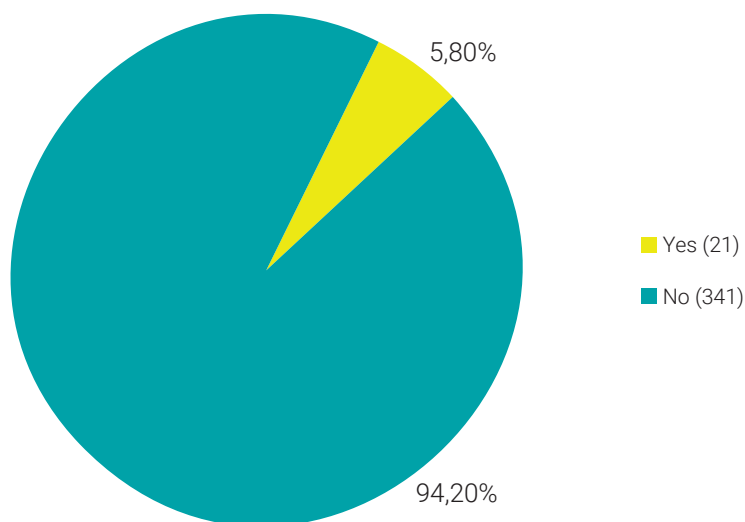


Figure 4. Results obtained for the second survey question

Source: own work

- Do you believe that the lack of adequate infrastructure in this sector affects user safety? (See Figure 5)

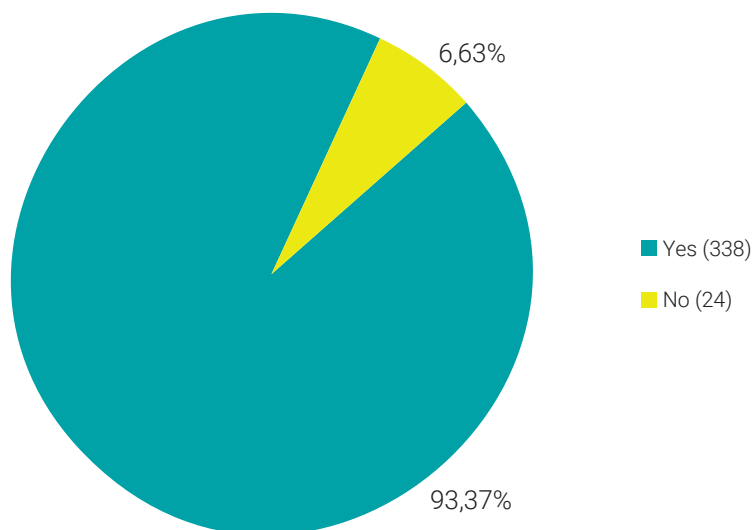


Figure 5. Results obtained for the third survey question.

Source: own work

- Do you consider the implementation of a bicycle lane necessary within this sector? (See Figure 6)

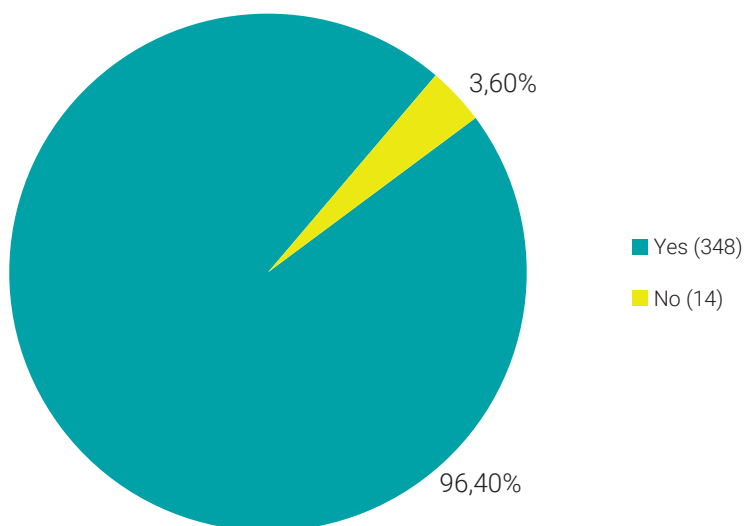


Figure 6. Results obtained for the fourth survey question.

Source: own work

- Would you use a bicycle lane along this corridor if it were implemented? (See Figure 7)

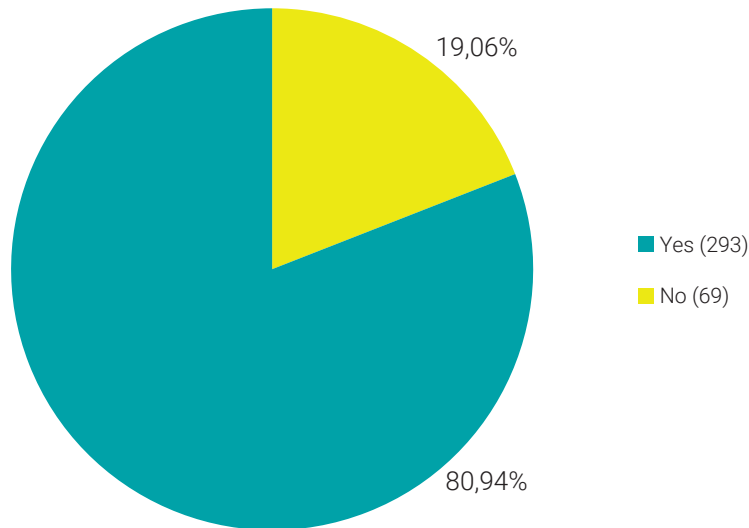


Figure 7. Results obtained for the fifth survey question.

Source: own work

The obtained results revealed that 94.2% of respondents perceive the corridor as unsafe for pedestrian and bicycle circulation, mainly due to the absence of adequate infrastructure and direct interaction with vehicular traffic. Likewise, 93.4% stated that the lack of cycling infrastructure negatively affects user safety. A high level of acceptance of the implementation of a bicycle lane was also identified, with 96.1% of respondents considering its implementation necessary and 80.9% stating that they would use the proposed infrastructure, representing approximately 293 potential users within the evaluated sample. Regarding corridor use, 35.1% of respondents reported using it several times per week, 32.9% daily, 22.1% occasionally, and only 9.9% indicated that they do not currently use it. These findings indicate a favorable potential demand for bicycle use as a mode of transport within the study area, consistent with previous studies related to active mobility, perceived safety, and transport accessibility [11].

Overall, this stage allowed the consolidation of a baseline diagnosis of the current corridor conditions through the integration of technical information and citizen perception, constituting a fundamental input for the subsequent stages of the study associated with the formulation and evaluation of design alternatives.

The implementation of the online survey with corridor users and bicycle commuters represented one of the principal mechanisms for collecting the baseline information required for the planning and evaluation of the proposed intervention. In general terms, the survey aimed to analyze the interaction between mobility dynamics and the urban conditions present within the study area, allowing the identification

of transportation indicators and their relationship with the surrounding urban environment. As a result, the collected information contributed to the establishment of urban mobility and design criteria for the proposed cycling infrastructure, as shown in Table 5.

Table 5. Profiles of cyclist user groups and travel modalities identified within the study corridor.

Type of Cyclist	Main Travel Purpose	Typical Trip Length	Travel Mode	Average Travel Speed
Daily urban cyclist	Work, school, personal activities, etc.	307 to 431 m per trip	Individual trips	15–20 km/h

Source: own work

3.3 Current Corridor Condition

The analyzed corridor along Carrera 22 presents a bidirectional roadway configuration with two vehicular lanes in each direction, separated by a central median with green areas. The evaluated section corresponds to an approximate length of 306.73 m in the Universidad Santo Tomás–Hacaritama direction and 430.94 m in the La Alborada–Universidad Santo Tomás direction. Each roadway direction consists of two traffic lanes with an approximate width of 3.65 m per lane, while the central median has an average width of 1.04 m. Likewise, the corridor currently includes lateral pedestrian infrastructure with an approximate variable width of 1.71 m. However, discontinuities, width reductions, and public space encroachments were identified at several points along the analyzed section.

From an urban perspective, the corridor is characterized by the presence of institutional, commercial, and service-related land uses that generate constant interaction among pedestrians, motorcyclists, public transport users, and private vehicle users. The roadway also includes lateral drainage channels located on the right side of each traffic direction. Nevertheless, incomplete sections and discharge points affecting the continuity of the surface drainage system were identified during the field inspections. Additionally, electrical utility poles and urban elements were found within potential intervention areas, constituting factors that directly influence the formulation of the proposed design alternatives. The current layout of the corridor is illustrated in Figure 8.

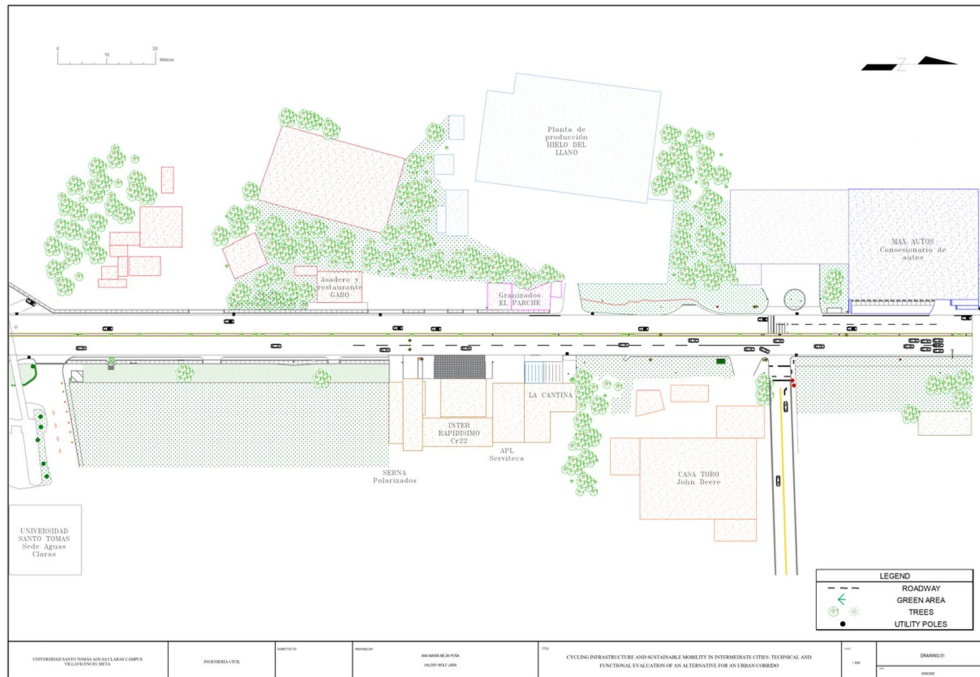


Figure 8. Current Corridor.

Source: own work

3.4 Selected Proposal

Two roadway intervention alternatives were formulated for the implementation of the proposed bidirectional bicycle lane within the study corridor. Both proposals considered the development of a bidirectional bicycle lane located on the sidewalk, together with pedestrian improvements, geometric adaptations, relocation of utility infrastructure, and optimization of surface drainage conditions. Nevertheless, the alternatives differ in the level of intervention required to ensure continuity, operational functionality, and user safety throughout the corridor.

The first alternative proposes the implementation of the bicycle lane through the adaptation and redistribution of the currently available pedestrian space without generating direct impacts on adjacent properties or existing structures within the corridor. The proposal includes a projected pedestrian facility with an approximate width of 1.2 m and a bidirectional bicycle lane with an estimated width of 2.04 m under ideal conditions. However, the continuity of both facilities is reduced along most sections of the corridor due to spatial restrictions. The intervention also includes earthworks, surface leveling, geometric sidewalk adaptations, relocation of electrical and telecommunication poles interfering with the proposed alignment, as well as the construction

and extension of lateral drainage channels with an approximate cross-sectional width of 0.6 m. Similar to the pedestrian and cycling facilities, the drainage system does not maintain full continuity throughout the corridor because of the limited available space. Although this alternative minimizes urban and property-related impacts by preserving the current operation of commercial establishments and existing structures, the technical analysis identified operational limitations associated with reduced roadway width in several segments. These constraints generate conflicts between pedestrians and cyclists, negatively affecting continuity, comfort, and perceived safety for non-motorized users. According to the *Guía de Cicloinfraestructura para Ciudades Colombianas* [12], cycling infrastructure should prioritize continuity, segregation, accessibility, and safety criteria in corridors with significant pedestrian and vehicular interaction.

The second alternative proposes a broader intervention aimed at consolidating a continuous and functionally segregated bidirectional bicycle lane throughout the entire corridor. This proposal includes a projected pedestrian facility with an approximate width of 1.2 m and lateral safety buffers of 0.1 m on each side, resulting in a total width of 1.4 m. Likewise, the bidirectional bicycle lane has an estimated width of 2.04 m, incorporating an additional 0.4 m safety buffer toward the roadway for a total width of 2.44 m. This configuration provides greater operational continuity, improved safety conditions, and a more balanced distribution of public space. The development of this alternative requires localized demolition, partial land acquisition, and the recovery of public space currently occupied by encroaching structures and informal occupations that restrict the continuity of pedestrian and cycling infrastructure. The proposal also incorporates earthworks, roadway geometric adaptations, relocation of electrical utility poles, and the construction of new lateral drainage channels with an approximate cross-sectional width of 0.6 m to optimize surface runoff management within the corridor.

Table 6. Comparative evaluation of Alternatives 1 and 2.

Criterion	Alternative 1	Alternative 2
Infrastructure continuity	Partial	Continuous
Pedestrian-cyclist segregation	Limited	Complete
Road safety conditions	Moderate	High
Operational functionality	Medium	High
Public space intervention	Low	High
Property acquisition	Not required	Localized acquisitions required

(continúa)

(viene)

Criterion	Alternative 1	Alternative 2
Utility relocation	Partial	Required
Compliance with the Colombian Cycling Infrastructure Guide	Partial	High
Selected alternative	No	Yes

Source: own work

The selection of the second alternative was primarily based on operational functionality, road safety, accessibility, and long-term corridor continuity criteria because network continuity is considered one of the principal requirements for low-stress cycling systems [29]. Previous studies on sustainable mobility and cycling infrastructure indicate that continuous and segregated cycling corridors significantly improve comfort, perceived safety, and operational efficiency for both pedestrians and cyclists [3], [12]. In this regard, the second proposal offers improved spatial organization and reduces direct conflicts among pedestrians, cyclists, and vehicular access points, creating more favorable conditions for active mobility within the study area.

The intervention is also supported by the provisions established in Law 1682 of 2013, specifically Article 19, which defines transportation infrastructure projects as matters of public utility and social interest, authorizing property acquisition and intervention processes when required for the development, improvement, or expansion of transportation infrastructure. Consequently, the recovery of occupied public space and the proposed roadway adaptations are justified as part of an intervention aimed at strengthening sustainable mobility, accessibility, and road safety conditions within the corridor.

The selected proposal and its general roadway configuration are presented in Figure 9, while Figure 10 illustrates the initial section of the bicycle lane in the Universidad Santo Tomás–Hacaritama direction, including the terminal section in the opposite direction. Figure 11 presents the roadway configuration near the intersection leading to the Hacaritama neighborhood, where commercial access points, public transport interaction, and operational continuity conditions in both directions of the corridor can be observed. Figure 12 shows the typical cross-sectional profile corresponding to the selected alternative, specifying the projected widths for pedestrian facilities, the bidirectional bicycle lane, separators, and the remaining geometric elements of the corridor.

All figures and geometric configurations developed for the proposal were based primarily on the technical criteria established in the *Guía de Cicloinfraestructura para*

Ciudades Colombianas [12] and the Colombian Road Signage Manual [15], incorporating the necessary adaptations according to the geometric, operational, and urban conditions specific to the study corridor.

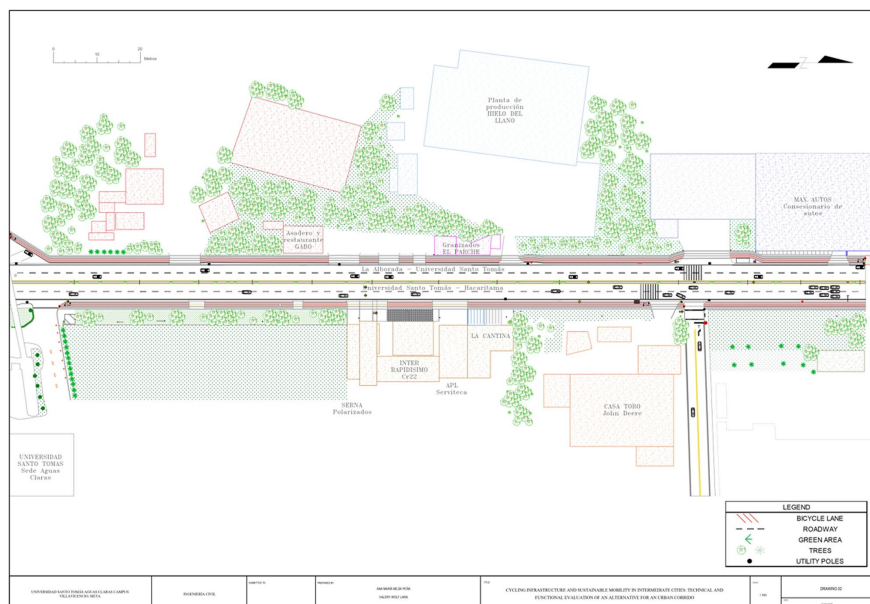


Figure 9. Layout of the selected proposal.

Source: own work

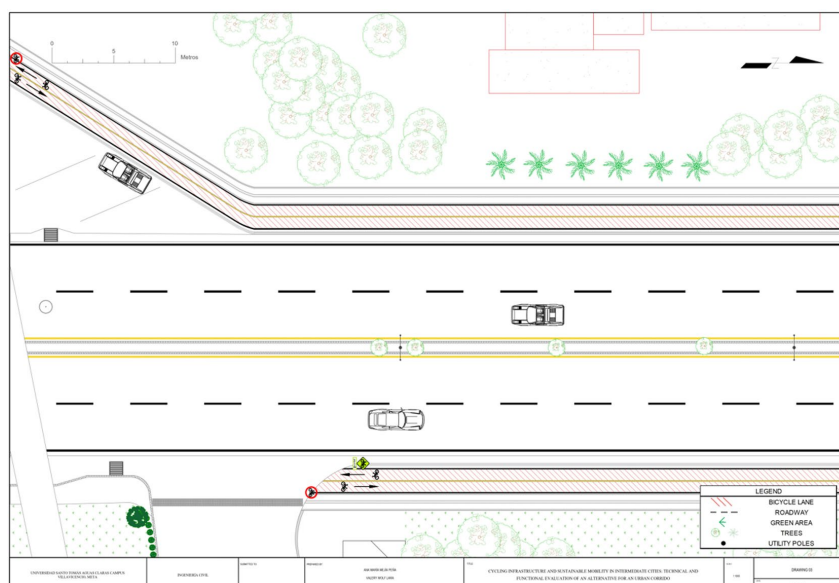


Figure 10. Start and end of a typical section of the selected proposal.

Source: own work

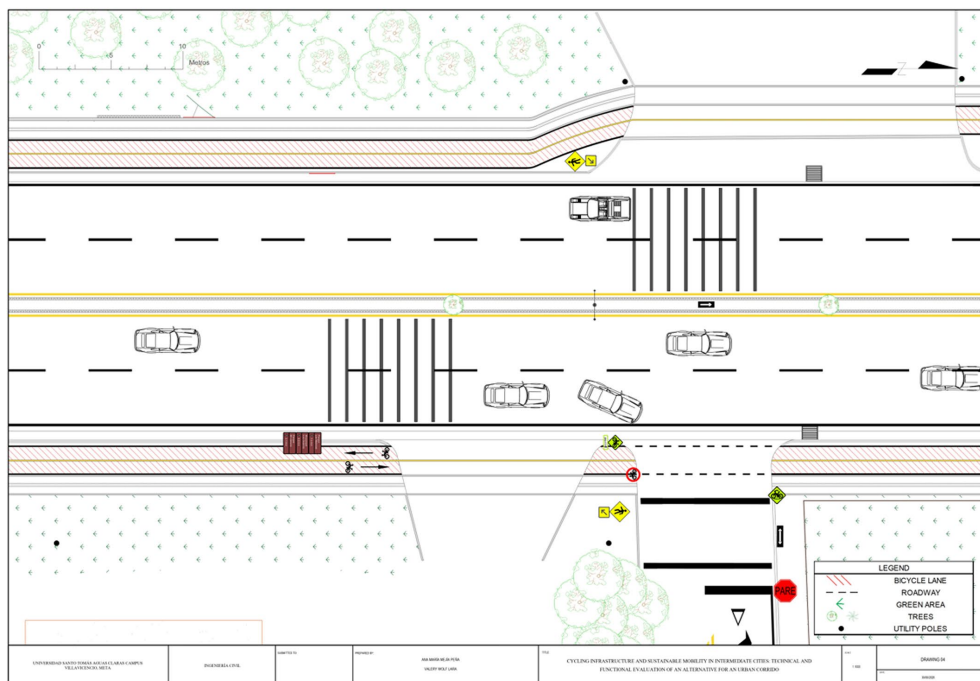


Figure 11. Roadway configuration near the intersection.

Source: own work

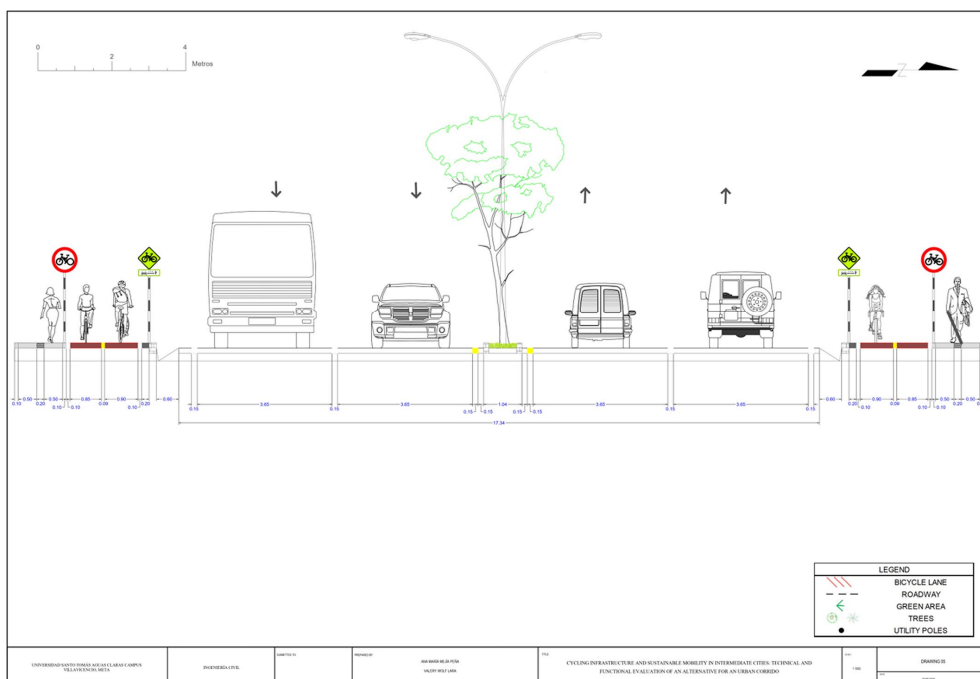


Figure 12. Typical cross-sectional profile.

Source: own work

3.5 Proposal Modeling

The selected alternative was evaluated through a traffic simulation process developed using PTV Vissim, which allowed the analysis of the operational performance of the corridor under the proposed geometric and functional configuration of the roadway and the bidirectional bicycle lane. The model was parameterized using the traffic volumes reported in Tables 1 and 2, the observed operating speeds, and field data describing the roadway geometry, the Hacaritama neighborhood access intersection, conflict areas, priority rules, and traffic signal timing. The simulation provided indicators related to average operating speed, average delay, number of stops, and overall traffic operating conditions, as presented in Table 6.

Table 6. Performance of the roadway network and bidirectional bicycle lane, PTV Vissim.

Sections	Roadway/Bicycle Lane	Existing Roadway
Section	1	1
SimRun	1	1
TimeInt	0-4200	0-4200
DelayAvg(All)	36,11	38,80
StopsAvg(All)	1,72	1,46
SpeedAvg(All)	19,23	18,26
DelayStopAvg(All)	11,77	12,80
DistTot(All)	406,96	406,96
TravTmTot(All)	76193,30	77397,40
DelayTot(All)	37263,26	38760,34
StopsTot(All)	1778	1463
DelayStopTot(All)	12149,90	12786,55
VehAct(All)	120	121
VehArr(All)	912	878
DelayLatent	157406,10	170024,90
DemandLatent	565	604

Source: own work

The results showed that the proposed bicycle lane scenario registered an average operating speed of 19.23 km/h, an average delay of 36.11 s, and a total of 1,778 stops during the simulation interval between 0 and 4,200 s. Compared with the existing roadway scenario, which recorded an average operating speed of 18.26 km/h, an average delay of 38.80 s, and 1,463 stops, the proposed scenario exhibited higher operating speeds and lower delay values. Likewise, the total travel time decreased

from 77,397.40 s to 76,193.30 s, while the total delay was reduced from 38,760.34 s to 37,263.26 s. Similarly, the average braking delay decreased from 12.80 s to 11.77 s, latent delay was reduced from 170,024.90 s to 157,406.10 s, and latent demand decreased from 604 to 565 users. In both scenarios, the total distance traveled remained constant at 406.96 km.

To facilitate the interpretation of these results, supplementary audiovisual material illustrating both the existing roadway conditions and the proposed bicycle lane scenario developed using PTV Vissim was prepared as complementary material associated with this study. The current corridor scenario can be accessed at <https://www.youtube.com/watch?v=Pe28sLXQITl>, while the proposed bicycle lane scenario is available at <https://www.youtube.com/watch?v=NMKKaoWspso>.

4. DISCUSSION

The study corridor presents deficiencies associated with the absence of segregated cycling infrastructure, pedestrian discontinuities, and conflicts among motorized and non-motorized users, conditions that negatively affect accessibility and road safety for vulnerable users and are commonly associated with lower levels of cycling comfort and safety [27].

Roadway width, public space occupation, and urban constraints highlight the importance of continuity and connectivity as fundamental conditions for the successful implementation of cycling infrastructure and the development of low-stress cycling networks [29], [31].

Citizen perception demonstrated broad support for the intervention and suggests that the principal barrier to bicycle use within the corridor is not the willingness to cycle but rather the absence of infrastructure capable of providing safe and continuous travel conditions. Similar conclusions have been reported in studies identifying perceived safety, accessibility, and infrastructure continuity as key determinants of bicycle adoption in urban environments [20], [28]. Comparable situations have also been documented in intermediate Colombian cities such as Pasto, where deficiencies in the continuity and accessibility of cycling infrastructure have limited the development of sustainable mobility alternatives [32].

The study also presents limitations that should be considered when interpreting the results. The analyses were conditioned by geometric restrictions, public space occupation, and limited roadway information in certain sections of the corridor. Likewise, the simulations were developed under specific operational assumptions and traffic conditions and therefore do not fully represent future variations associated with urban

growth or changes in travel demand. Consequently, the findings should be interpreted as a technical assessment of the current corridor conditions rather than as results directly generalizable to other urban contexts. From an implementation perspective, the intervention would require detailed engineering studies, the recovery of occupied public space in critical sections, institutional coordination, and financing mechanisms to support construction and long-term maintenance.

5. CONCLUSIONS

This study demonstrated that the evaluated corridor presents suitable technical and territorial conditions for incorporating a bidirectional bicycle lane, although its implementation requires different intervention strategies according to the roadway characteristics in each travel direction. The proposed alternative is consistent with the sustainable mobility objectives established for Villavicencio and represents a feasible strategy for improving active transportation along a strategic urban corridor.

The integration of field surveys, traffic counts, and microscopic traffic simulation provided complementary evidence supporting the proposed intervention. Citizen perception revealed a strong demand for safer cycling infrastructure, while the operational analysis showed that reallocating roadway space can be achieved with improvements in key traffic performance indicators, including average operating speed, delay, and latent demand, without substantially affecting corridor operation.

Beyond evaluating a specific corridor, this research proposes an integrated methodological approach that combines territorial, operational, and social analyses to support bicycle infrastructure planning in intermediate cities. This framework may serve as a technical reference for future sustainable mobility projects developed under similar urban conditions [26].

REFERENCES

- [1] United Nations, *World Urbanization Prospects 2025*. New York, NY, USA: United Nations, 2025. [Online]. Available: <https://population.un.org/wup/>
- [2] D. Vale, M. Pereira, and F. M. Viana, "Different destination, different commuting pattern? Analyzing the influence of the built environment on commuting by bicycle in medium-sized cities," *Journal of Transport Geography*, vol. 76, pp. 118–129, 2019, doi: <https://doi.org/10.1016/j.jtrangeo.2019.03.005>.

- [3] S. Gössling and S. McRae, "Subjectively safe cycling infrastructure: New insights for urban design," *Journal of Transport Geography*, vol. 101, Art. no. 103340, 2022, doi: <https://doi.org/10.1016/j.jtrangeo.2022.103340>.
- [4] Netherlands Institute for Transport Policy Analysis, *Cycling Facts 2020*. The Hague, The Netherlands: Netherlands Institute for Transport Policy Analysis, 2020. [Online]. Available: <https://english.kimnet.nl/>
- [5] City of Copenhagen, *Bicycle Account 2022*. Copenhagen, Denmark: City of Copenhagen, 2022. [Online]. Available: <https://www.kk.dk/>
- [6] C. M. Gaete, "The world's longest elevated cycling path opens in China," *ArchDaily*, Sep. 14, 2017. [Online]. Available: <https://www.archdaily.com/806710/the-worlds-longest-elevated-cycling-path-opens-in-china>
- [7] J. M. Vassallo and P. C. Bueno, *Transport Challenges in Latin American Cities: Lessons Learnt from Policy Experiences*. Washington, DC, USA: Inter-American Development Bank, 2019, doi: <https://doi.org/10.18235/0001558>.
- [8] Secretaría Distrital de Movilidad de Bogotá, *Red de Ciclorrutas de Bogotá*. Bogotá, Colombia: Secretaría Distrital de Movilidad, 2023. [Online]. Available: <https://www.movilidadbogota.gov.co/web/>
- [9] A. Schwedhelm, "Biking provides a critical lifeline during the coronavirus crisis," World Resources Institute, Apr. 17, 2020. [Online]. Available: <https://www.wri.org/insights/biking-provides-critical-lifeline-during-coronavirus-crisis>
- [10] Alcaldía de Villavicencio, *Plan de Ordenamiento Territorial de Villavicencio*. Villavicencio, Colombia: Alcaldía de Villavicencio, 2015. [Online]. Available: <https://www.villavicencio.gov.co/>
- [11] T. Litman, *Evaluating Transportation Equity*. Victoria, BC, Canada: Victoria Transport Policy Institute, 2020. [Online]. Available: <https://www.vtpi.org/equity.pdf>
- [12] Ministerio de Transporte, *Guía de cicloinfraestructura para ciudades colombianas*. Bogotá, Colombia: Ministerio de Transporte, 2018. [Online]. Available: <https://www.mintransporte.gov.co/>
- [13] N. da Silveira Arruda, H. D. González Zapata, and A. M. Navia Hermida, "Sustainable mobility through knowledge exchange and collaborative mapping of cycling infrastruc-

- re: SIGenBici in Medellín, Colombia,” in *Communications in Computer and Information Science*, vol. 1594. Cham, Switzerland: Springer, 2022, pp. 261–274, doi: https://doi.org/10.1007/978-3-031-05182-1_19.
- [14] A. Nikitas, S. Tsigdinos, C. Karolemeas, E. Kourmpa, and E. Bakogiannis, “Cycling in the era of COVID-19: Lessons learnt and best practice policy recommendations for a more bike-centric future,” *Sustainability*, vol. 13, no. 9, Art. no. 4620, 2021, doi: <https://doi.org/10.3390/su13094620>.
- [15] Ministerio de Transporte and Agencia Nacional de Seguridad Vial, *Manual de Señalización Vial de Colombia: Dispositivos uniformes en la infraestructura vial para la regulación del tránsito y la seguridad vial*. Bogotá, Colombia: Ministerio de Transporte, 2024. [Online]. Available: <https://ansv.gov.co/>
- [16] Alcaldía de Villavicencio, “Pico y placa 2026 para vehículos particulares en Villavicencio,” 2026. [Online]. Available: <https://villavicencio.gov.co/con-jornadas-pedagogicas-inicio-el-pico-y-placa-2026-para-vehiculos-particulares-en-villavicencio/>
- [17] L. X. Rojas Calderón, “Planificando el crecimiento urbano de una ciudad intermedia: Consideraciones críticas sobre el POT de Villavicencio,” M.S. thesis, Centro Interdisciplinario de Estudios sobre Desarrollo, Universidad de los Andes, Bogotá, Colombia, 2020, doi: <https://doi.org/10.57784/1992/48628>.
- [18] T. van Laake, J. S. Gómez-Rodríguez, J. F. Bustos, N. Lleras, and D. Pérez-Rodríguez, “From the sidewalk to the carriageway: The evolution of cycling infrastructure design and policy in Colombian cities,” *Ciudad y Territorio Estudios Territoriales*, vol. 57, no. 226, pp. (ND), 2025, doi: <https://doi.org/10.37230/CyTET.2025.226.13>.
- [19] G. A. Barrero and A. Rodríguez-Valencia, “Asking the user: A perceptual approach for bicycle infrastructure design,” *International Journal of Sustainable Transportation*, vol. 16, no. 3, pp. 246–257, 2022, doi: <https://doi.org/10.1080/15568318.2020.1871127>.
- [20] M. Branion-Calles, T. Nelson, D. Fuller, L. Gauvin, and M. Winters, “Associations between individual characteristics, availability of bicycle infrastructure, and city-wide safety perceptions of bicycling,” *Transportation Research Part A: Policy and Practice*, vol. 123, pp. 229–239, 2019, doi: <https://doi.org/10.1016/j.tra.2018.10.024>.
- [21] S. Cafiso, G. Pappalardo, and N. Stamatiadis, “Observed risk and user perception of road infrastructure safety assessment for cycling mobility,” *Transportation Research Record*, vol. 2674, no. 8, pp. 134–145, 2020, doi: <https://doi.org/10.1177/0361198120915604>.

- [22] S. Useche, L. Montoro, F. Alonso, and O. Oviedo-Trespalacios, "Infrastructural and human factors affecting safety outcomes of cyclists," *Sustainability*, vol. 10, no. 2, Art. no. 299, 2018, doi: <https://doi.org/10.3390/su10020299>.
- [23] B. Adinarayana and B. Kasinayana, "Bicycle safety index for bicycle level of service on urban streets with extreme mixed weather conditions," *Innovative Infrastructure Solutions*, vol. 7, no. 4, Art. no. 248, 2022, doi: <https://doi.org/10.1007/s41062-022-00853-5>.
- [24] J. A. Montoya, D. A. Escobar, and C. A. Moncada, "Accessibility conditions of private motorized transport considering the proposal of construction of a cycling infrastructure," *Información Tecnológica*, vol. 32, no. 5, pp. 45–56, 2021, doi: <https://doi.org/10.4067/S0718-07642021000500045>.
- [25] A. F. Lowry, M. S. Callister, B. Gresham, and M. Moore, "Assessment of communitywide bikeability with bicycle level of service," *Transportation Research Record*, vol. 2314, no. 1, pp. 41–48, 2012, doi: <https://doi.org/10.3141/2314-06>.
- [26] J. Pucher and R. Buehler, *City Cycling*. Cambridge, MA, USA: MIT Press, 2012, doi: <https://doi.org/10.7551/mitpress/8472.001.0001>.
- [27] C. Reynolds, M. Harris, K. Teschke, P. A. Crompton, and M. Winters, "The impact of transportation infrastructure on bicycling injuries and crashes," *Environmental Health*, vol. 8, Art. no. 47, 2009, doi: <https://doi.org/10.1186/1476-069X-8-47>.
- [28] M. Winters, G. Davidson, D. Kao, and K. Teschke, "Motivators and deterrents of bicycling: Comparing influences on decisions to ride," *Transportation*, vol. 38, no. 1, pp. 153–168, 2011, doi: <https://doi.org/10.1007/s11116-010-9284-y>.
- [29] P. Furth and M. Mekuria, "Network connectivity for low-stress bicycling," *Transportation Research Record*, vol. 2587, no. 1, pp. 41–49, 2016, doi: <https://doi.org/10.3141/2587-06>.
- [30] J. Dill and T. Carr, "Bicycle commuting and facilities in major U.S. cities: If you build them, commuters will use them," *Transportation Research Record*, vol. 1828, no. 1, pp. 116–123, 2003, doi: <https://doi.org/10.3141/1828-14>.
- [31] A. Hull and K. O'Holleran, "Bicycle infrastructure: Can good design encourage cycling?" *Urban, Planning and Transport Research*, vol. 2, no. 1, pp. 369–406, 2014, doi: <https://doi.org/10.1080/21650020.2014.955210>.

- [32] M. L. Carrasco Villota, *Diagnóstico de la infraestructura para el uso de la bicicleta en la planeación urbanística para la movilidad sostenible: Caso de estudio de los tramos de ciclovías en la ciudad de Pasto (2000–2021)*, M.S. thesis, Universidad Nacional de Colombia, Pasto, Colombia, 2023. [Online]. Available: <https://repositorio.unal.edu.co/handle/unal/84980>