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SUSTAINABLE MOBILITY AND TERRITORIAL ACCESSIBILITY IN MANIZALES, COLOMBIA: SOCIAL COST-BENEFIT ANALYSIS OF AN EXPANDED AERIAL CABLE NETWORK

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Abstract: This research evaluates the socioeconomic feasibility of expanding the aerial cable car system in Manizales and Villamaría, Colombia, through a Social Cost-Benefit Analysis (SCBA). The assessment compares the three operational lines with a projected nine-line network, based on the Manizales Land Use Plan. The objective is to quantify and monetize impacts on CO2eq emissions, territorial accessibility, road safety, and public health benefits derived from induced active mobility. A quantitative evaluative approach was employed to compare baseline and projected scenarios using geospatial analysis (Kriging interpolation) and multimodal transport modeling in TransCAD. The baseline integrates the 2017 origin-destination matrix for 255 traffic analysis zones and georeferenced road crash records from 2020 to 2024. Station catchment areas were delineated using ten-minute walking isochrones. The WHO Health Economic Assessment Tool (HEAT) was utilized to monetize health externalities, while road safety was assessed through a risk exposure model. The project yielded a positive Economic Net Present Value (ENPV) of 21951675.75 USD and a Benefit-Cost Ratio (BCR) of 1.41 over a 15-year horizon. The central appraisal adopts a 9% social discount rate. Public health benefits represent the most significant impact, accounting for 84.2% of the total social contribution and preventing an estimated 564 premature deaths through increased physical activity. The network expansion is socioeconomically viable, functioning as a transportation "Backbone" that mitigates territorial inequalities and reduces road fatalities by 32.1%. The future scenario also projects a 41.0% reduction in injuries, 5,865 tonnes of CO_2-equivalent emissions avoided annually (9.4%), and travel-time savings of up to 19% in the most benefited areas. It constitutes a robust strategy for urban decarbonization and public health promotion, justifying the allocation of public resources for sustainable infrastructure.

Keywords: Social Cost-Benefit Analysis, aerial cable, sustainability, accessibility, mobility

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INTRODUCTION

Sustainable mobility is a key challenge in contemporary urban planning, requiring cities to balance travel demand with environmental sustainability and social equity (Tantaleán, 2024; Tanikawa-Obregón & Paz-Gómez, 2021). In this context, modal shift strategies promote active mobility and mass transit as alternatives to reduce transport externalities such as congestion, noise, air-quality deterioration, and greenhouse gas emissions (Reyes-Vásquez et al., 2021; World Health Organization, 2024). These positive externalities, particularly emission reductions, can be monetized and incorporated into project appraisal as indicators of social profitability. Accessibility is also central to infrastructure assessment, as it reflects the ease of reaching urban opportunities and supports a more equitable distribution of transport benefits (López-Escolano & Pueyo-Campos, 2019; Cardoso & Carñel, 2024). Therefore, transport appraisal should not be limited to financial feasibility, but should also account for broader social, environmental, health, and territorial impacts.

Within this framework, Latin America has become the global leader in urban Aerial Cable Car (ACC) systems, accounting for 62% of the world's mass-transit cable lines (Cardona-Urrea et al., 2023). Since the opening of Medellín's Metrocable in 2004, ACC systems have reshaped mobility in hillside urban areas by connecting steep, peripheral, and historically underserved neighborhoods with the formal transport network (Brand & Dávila, 2011).

The Medellín case showed that ACC systems can improve access for low-income users and support urban integration when combined with broader public-space and social urbanism strategies (Bocarejo et al., 2014).

More recent evidence from Bogotá has also shown that ACC systems can influence user expectations, perceived accessibility, satisfaction, activity participation, air-pollution exposure, and first- and last-mile travel behavior (Guzman et al., 2023; Morales-Betancourt et al., 2023; Guzman et al., 2025; Cardona-Urrea et al., 2026).

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ACC systems can operate either as feeder modes, as in Medellín and Bogotá, or as transport backbones in steep cities where cable networks structure public transport, such as La Paz and Manizales (Cardona-Urrea et al., 2023). In Manizales, Colombia, the ACC currently operates three lines that constitute the baseline scenario of this study: Line 1, Cámbulos-Fundadores; Line 2, Cámbulos-Villamaría; and Line 3, Cámbulos-El Cable. The city's Land Use Plan projects an expanded network composed of nine lines, which would consolidate the ACC as a central component of the urban transport system. This planned expansion is particularly relevant due to the city's steep topography, spatial fragmentation, and mobility constraints, which make conventional surface transport less efficient in several urban corridors.

Previous studies in Manizales have assessed the ACC system through analytical, simulation, accessibility, and environmental approaches. Escobar et al. (2015) evaluated the operating cable system using performance, simulation, and urban accessibility methods, while Escobar et al. (2022) estimated the impact of a new aerial cable-car project on accessibility and CO_2 emissions, considering socioeconomic strata. Evidence from Bogotá also shows that ACC systems can promote physical activity through first- and last-mile walking, while SCBA applications in steep terrain have reported benefit-cost ratios driven mainly by health and safety externalities (Baldovino-Chiquillo et al., 2023; Cardona-Urrea et al., 2023). These studies show that ACC systems can improve accessibility, reduce emissions, influence physical activity, and generate social benefits; however, they do not fully integrate road safety, public health through HEAT, emissions, and territorial accessibility within a single socioeconomic appraisal framework. Taken together, this evidence suggests that ACC systems should be evaluated beyond conventional transport indicators. In mountainous and topographically constrained cities, their potential impacts extend to accessibility, public health, road safety, environmental performance, and territorial equity. However, these dimensions are often assessed separately, limiting the understanding of their combined contribution to social welfare.

Social Cost-Benefit Analysis (SCBA) provides the necessary framework to internalize these externalities through shadow prices, the Social Value of Time, and the monetary valuation of non-market benefits (Hernández-Díaz, 2019). Therefore, the main aim of this paper is to evaluate the socioeconomic viability of expanding the ACC network in Manizales, Colombia, from the current three-line baseline to the projected nine-line system, through an ex ante SCBA. By integrating road safety, public health benefits from active mobility, CO_2-equivalent emission reductions, and territorial accessibility gains, this study assesses whether the ACC expansion constitutes a socially profitable investment and whether it can operate as a sustainable transport backbone for a topographically constrained intermediate city.

MATERIALS AND METHODS

This research adopts a quantitative, applied, and *ex ante* evaluation approach to assess the socioeconomic viability of expanding the Aerial Cable Car (ACC) network in Manizales, Colombia. The analytical workflow is organized into six sequential stages, integrating multimodal transport modeling, geospatial analysis, and Social Cost-Benefit Analysis (SCBA). (Figure 1).

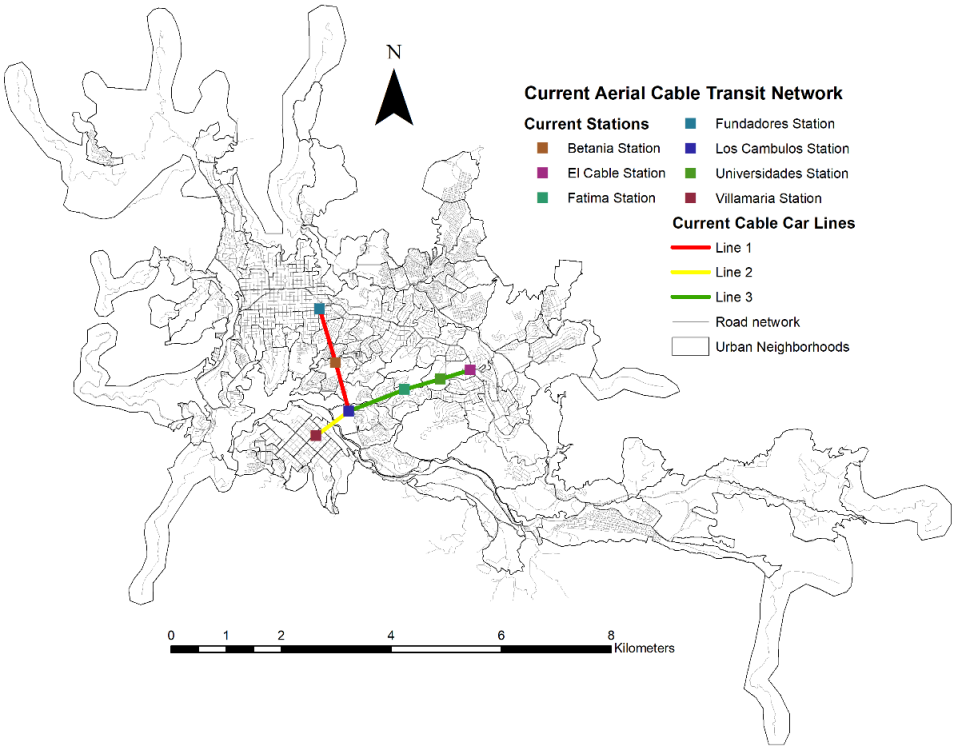


Figure 1. Aerial Cable Car (ACC) network: current scenario (Source: Own elaboration)

Phase 1: Input Characterization and Baseline

The baseline was consolidated using five main data sources. First, the official Origin-Destination (OD) Matrix (2017) was used to represent daily trips between 255 Traffic Analysis Zones (TAZs). Second, the road and pedestrian network was built from OpenStreetMap, comprising 12.798 links and 50.827 nodes. Third, operational parameters included a walking

speed of 1.19 m/s (4.28 km/h) (Guío-Burgos & Poveda D'Otero, 2015) and an ACC operating speed of 18 km/h based on real-time data from Lines 1, 2, and 3, which constitute the current baseline. Fourth, fuel efficiency and emission factors were obtained from the UPME (2018). Fifth, georeferenced crash records for the 2020–2024 period were provided by the National Road Safety Agency (ANSV). Regarding the inclusion of 2020 data—a year marked by COVID-19 lockdowns—the decision to retain these records is methodologically grounded in two reasons: (i) it allows for observing the "rebound effect" in road safety after restrictions were lifted in 2021-2022, and (ii) it functions as a control scenario of "low risk exposure," validating the hypothesis that reducing motorized surface traffic directly impacts life preservation.

Phase 2: Accessibility and Catchment Modelling

Multimodal network models were developed in TransCAD 4.5 and ArcMap 10.5. The future scenario includes 9 projected ACC lines and 17 stations (Figure 2), while the baseline comprises the 3 currently operational lines. Travel time was estimated using total time as impedance. Catchment areas were defined using 10-minute pedestrian isochrones (approximately 714 meters), a threshold validated as the maximum distance users are willing to walk to reach an ACC station. A recognized limitation of this model is that Global Average Accessibility was calculated focusing exclusively on the integration of the road network, pedestrian links, and the ACC system.

Although traditional buses (Public Collective Transport - TPC) represent 32.4% of daily trips in Manizales, they were not modeled as an independent layer with frequencies and routes. Therefore, results reflect the ACC's performance as a sustainable backbone rather than a full systemic integration with the TPC.

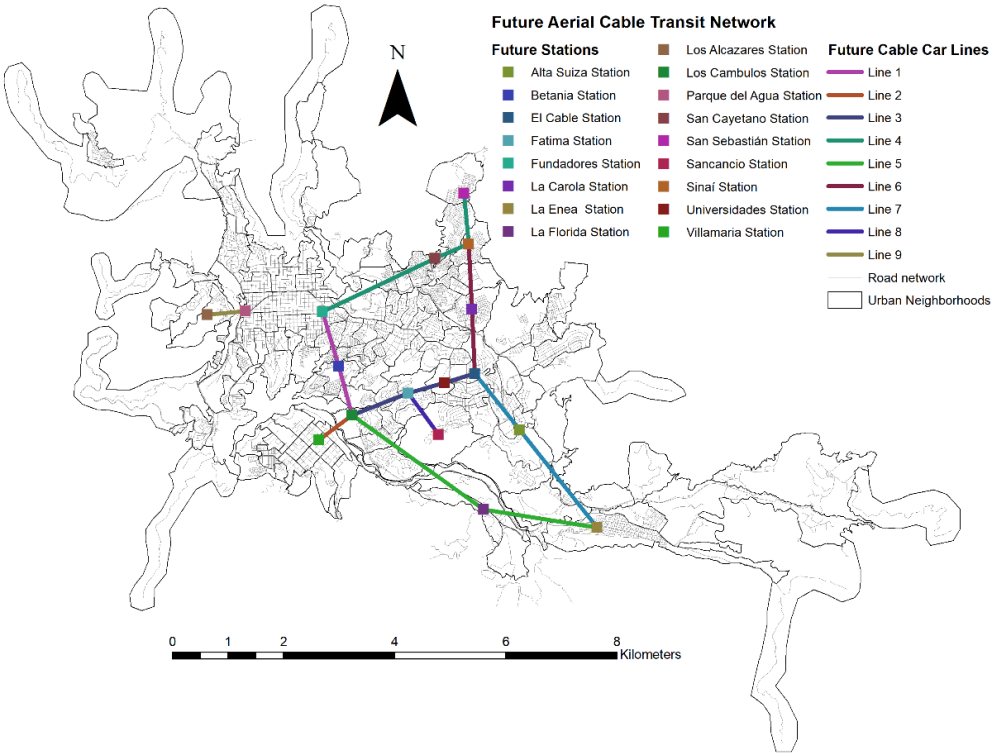


Figure 2. Aerial Cable Car (ACC) network: future scenario (Source: Own elaboration)

Phase 3: Environmental Analysis (Emissions)

Environmental impacts were estimated by comparing motorized travel demand across scenarios. CO2-equivalent emissions (*Eij*) were estimated based on energy demand (*Fik*) derived from fuel efficiency (*Ckl*), calorific values (*Vck*), and emission factors (*FEkj*) (Escobar et al., 2022). In the future scenario, a Modal Shift Factor (Conversion Factor - *CF*) of 50.58% was applied, representing the attractiveness of the ACC to users currently using private vehicles, taxis, and motorcycles. The calculations follow Equations 1 to 6 (Escobar et al., 2022):

$$VT_i = \frac{\sum_{q=1}^{n} V_{il} * Dqn}{\sum_{q=1}^{n} V_{il}} \quad (1)$$

$$F_{ik} = \sum_{l} V_{il} * V_{ck} * \frac{VT_i}{C_{kl}} \quad (2)$$

$$E_{ij} = \sum_{k} F_{ik} * FE_{kj} \quad (3)$$

$$\mathrm{CF} = \frac{V_{ac}}{V_c + V_{mot} + V_t} \quad (4)$$

$$V_{i(S)} = \mathrm{CF} * V_{i(pmt)} \quad (5)$$

$$V_{il(fut)} = Current\ scenario\ trips - Displaced\ trips = V_{il(act)} - V_{i(S)} \quad (6)$$

where VTi denotes the average trip distance (km/trip); vil, annual trips by vehicle type l; Dqn, minimum distance between TAZs q and n (km); Fik, energy demand by fuel type k (TJ); Vck, calorific value of fuel k (TJ/gal); Ckl, fuel efficiency of vehicle type l using fuel k (km/gal); EijE, CO_2-equivalent emissions (tons/year); FEkj, emission factor of pollutant j for fuel k (kg/TJ); CF, modal conversion factor; and Vi(S), motorized trips displaced to the ACC system (trips/year).

Phase 4: Road Safety Assessment

Road safety impacts were estimated from the expected reduction in exposure to motorized traffic risk. Generic fatality risk (*FRgeneric*) and projected casualties (*Flocal*) are calculated as shown in Equations 7 and 8 (World Health Organization, 2024):

$$FR_{generic} = \frac{Local\ Victims\ per\ Year}{Total\ Distance\ Traveled\ per\ Year} \quad (7)$$

$$F_{local} = FR_{generic} * D_{local} \quad (8)$$

where FRgeneric denotes the fatality risk per distance unit (fatalities/km); Local Victims, the average annual fatalities observed in the study area; Total Distance Traveled, the baseline annual vehicle-kilometers (km/year); Flocal, the expected fatalities in the future scenario (fatalities/year); and Dlocal, the projected annual distance traveled after modal shift (km/year).

Phase 5: Accessibility and Health Assessment

Global average accessibility (*Ai*) was calculated using Equation 9 (Escobar et al., 2022). Health benefits were estimated using the WHO's HEAT framework to quantify the Relative Risk Reduction (*RRr*) in Equation 12 (World Health Organization, 2024):

$$A_i = \frac{\sum_{j=1}^{n} t_{ij}}{n-1} \quad (9)$$

$$Tv_{savings} = Tv_{Global_current} - Tv_{Global_future} \quad (10)$$

$$PerTv_{savings} = \left(Tv_{savings}/Tv_{Global_current}\right) * 100 \quad (11)$$

$$RR_r = \left[(1 - RR) * \left(\frac{Local\ walking\ and\ cycling\ volume}{Reference\ walking\ and\ cycling\ volume}\right)\right] * 100 \quad (12)$$

where Ai denotes the average travel time from node i to all other destinations (minutes); tij, the minimum travel time between nodes i and j (minutes); Tvsavings, the absolute travel-time reduction (minutes); RRr, the reduction in all-cause mortality risk (%); RR, the relative risk parameter, set at 0.89 for walking and 0.90 for cycling; and Local volume, the average annual distance walked or cycled per person (km/person/year).

Phase 6: Comprehensive Socioeconomic Assessment (SCBA)

All impacts were monetized and integrated into an SCBA over a 15-year horizon. The Economic Net Present Value (*ENPV*) is estimated using Equation 13 (Hernández-Díaz, 2019):

$$\mathrm{ENPV} = \sum_{t=0}^{n} \frac{Economic\ benefits - Economic\ Costs}{(1 + SDR)^t} \quad (13)$$

where ENPV denotes the net social wealth generated at period zero (USD); EconomicBenefitst, the monetized health, safety, environmental, and accessibility benefits in year t; and SDR, the social discount rate. In line with Resolution 1092 of 2022, Colombia's official Social Discount Rate (SDR) of 9.0% was adopted as the central case. Sensitivity analyses using 6% and 12% were also performed to assess the robustness of project viability under alternative discounting assumptions.

RESULTS AND DISCUSSION

Investment Costs and Implementation Phases

The ACC network expansion requires an estimated investment of USD 506.4 million for 21.3 km of additional infrastructure, equivalent to USD 23.77 million/km. This estimate is based on the actual execution cost of Line 3 in Manizales, completed in 2025, which reached 55.4 million USD, or 23.77 million USD/km. The baseline cost includes electromechanical systems, station civil works, and complementary urban interventions. According to the POT 2017–2031, the expansion is planned in short-, medium-, and long-term phases, which is relevant because several benefits, particularly health gains, require gradual maturation. The investment also includes social urbanism interventions around stations, such as pedestrian infrastructure and public-space improvements to support accessibility and safety.

Road Safety Impacts: Reductions and Internalization

The ACC expansion operates as a segregated transport system, reducing conflict points between motorized traffic and vulnerable road users. The analysis projects a 32.1% potential reduction in fatalities and a 41.0% decrease in injuries within the 10-minute station catchment areas (Figures 3 and 4), which is particularly relevant since pedestrians and motorcyclists account for 80% of fatalities in Manizales. These benefits were monetized using a Value of Statistical

Life (VSL) adjusted to 2024 prices of USD 1.06 million, a VSL per year of USD 38397, and a unit injury cost of USD 355. This internalization of road safety as an economic benefit is consistent with Osorio-García et al. (2023), who emphasize the role of segregated infrastructure in contexts with risky pedestrian behavior.

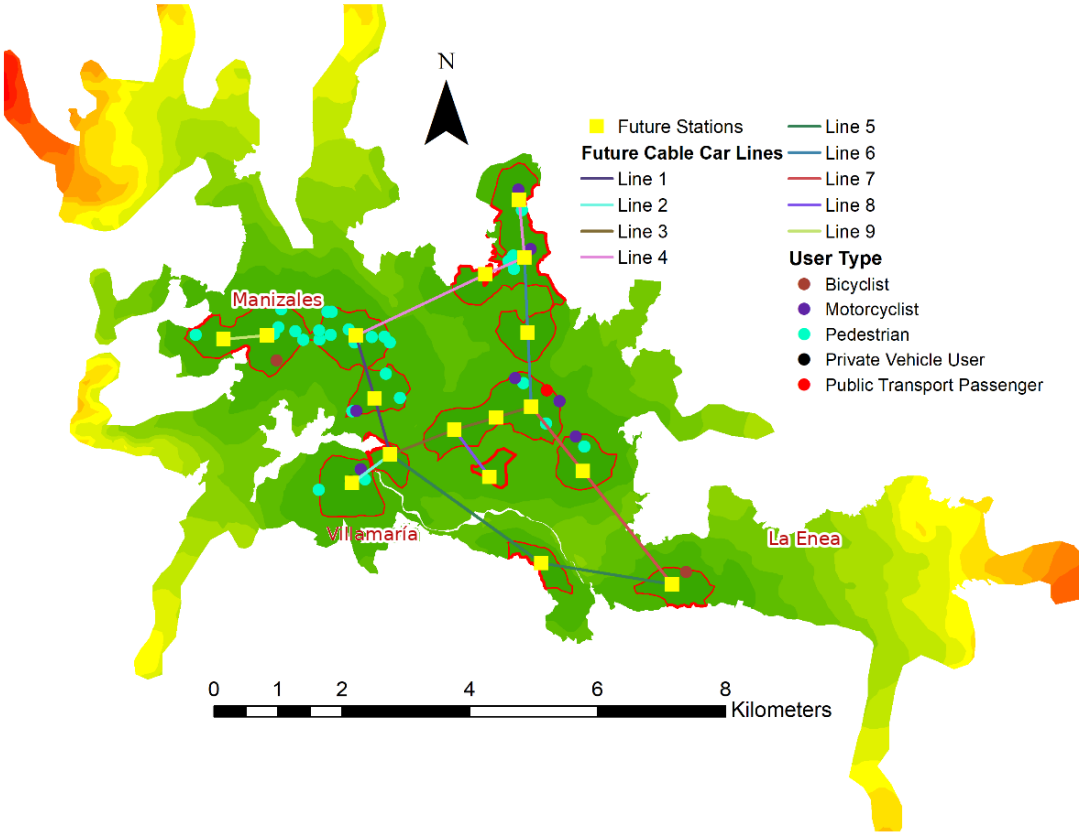


Figure 3. Projected reduction in road traffic fatalities under the future scenario (Source: Own elaboration)

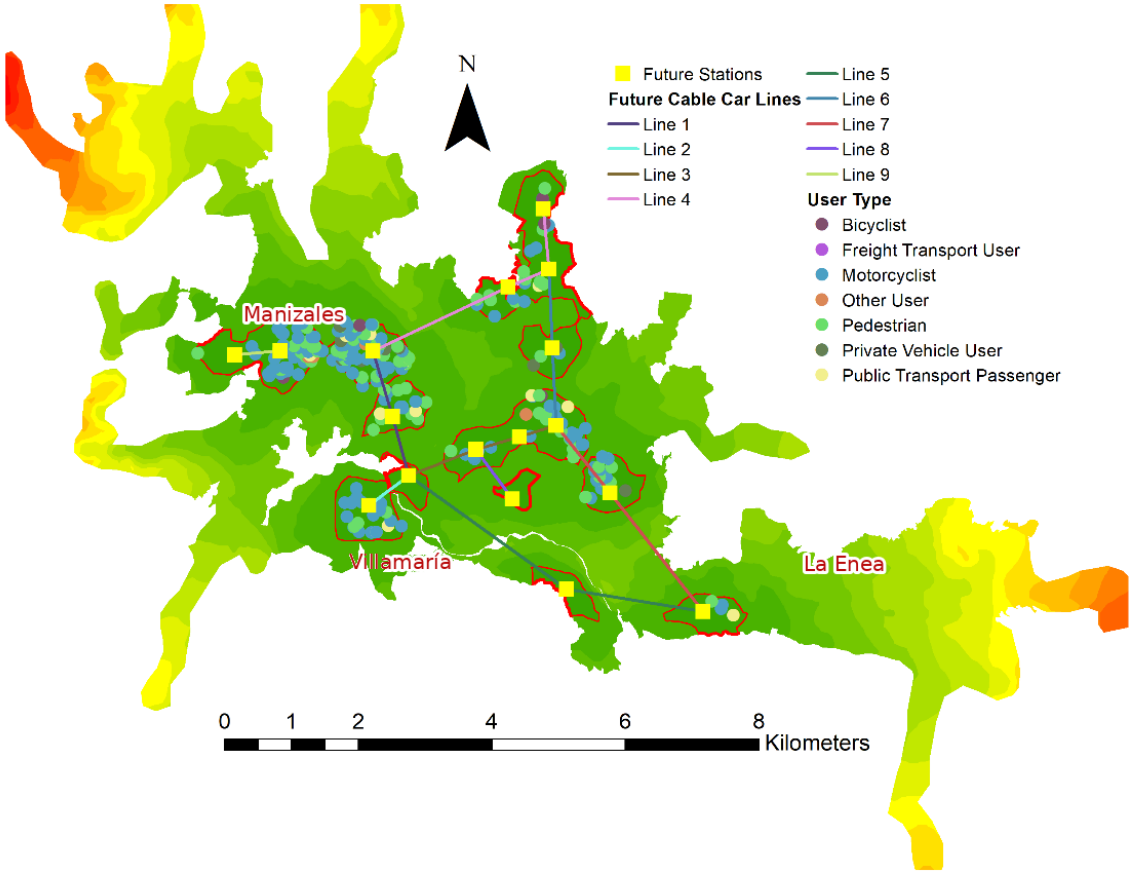


Figure 4. Projected reduction in road traffic injuries under the future scenario (Source: Own elaboration)

Environmental and Decarbonization Potential

The future scenario reduces annual CO_2-equivalent emissions by 9.4%, equivalent to 5865 tons of CO_2eq per year. Monetized using Colombia's Social Cost of Carbon of USD 67.4/tCO_2eq, this represents an annual social saving of USD 395503. Although it accounts for only 0.83% of total monetized benefits, it confirms the ACC's contribution to urban decarbonization by shifting demand away from carbon-intensive modes such as private cars and motorcycles.

Territorial Accessibility and Socioeconomic Distribution

Global average accessibility improves by up to 19% in the most benefited areas (Figure 5). Travel-time savings were monetized using a segmented Social Value of Time (SVT): USD 5.2/h for high-income users, USD 2.4/h for middle-income users, and USD 1.1/h for low-income users. Results show that Socioeconomic Stratum 3 is the largest beneficiary, accounting for 43.6% of the covered population and 46.6% of total time saved (Figure 6), while Stratum 4 records gains comparable to Stratum 2. This indicates that the ACC expansion benefits both middle-income and peripheral sectors, reinforcing its role as a backbone for territorial accessibility and spatial justice, consistent with evidence from the "Mi Teleférico" system in La Paz, Bolivia (Martínez et al., 2024).

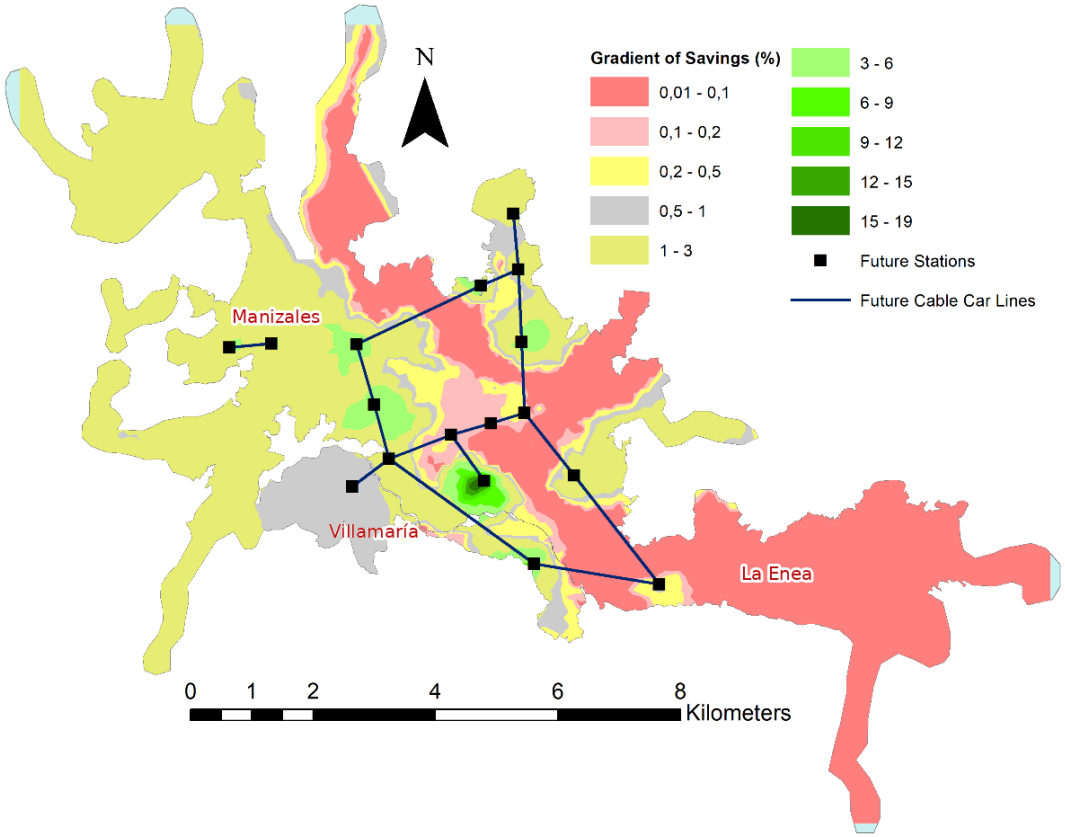


Figure 5. Gradient of percentage travel time savings in global average accessibility under the future scenario (Source: Own elaboration)

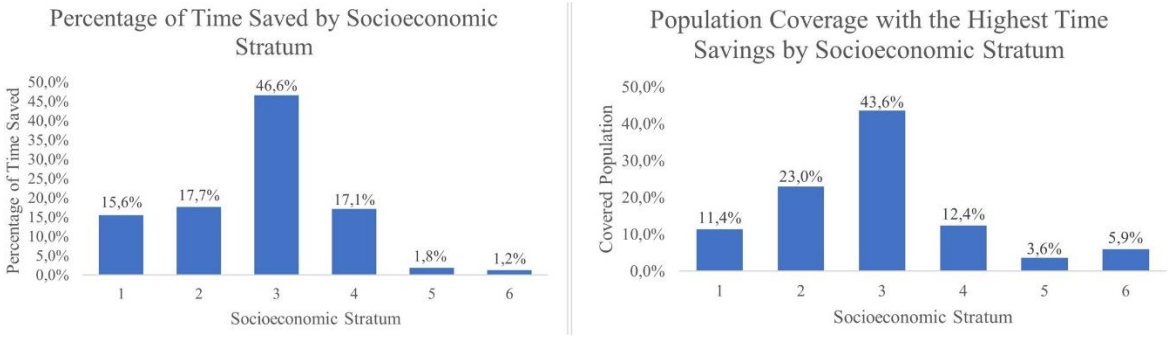


Figure 6. Territorial accessibility impact; (a) Percentage of Time Saved by Socioeconomic Stratum; (b) Population Coverage with the Highest Time Savings by Socioeconomic Stratum (Source: Own elaboration)

Public Health Gains from Active Mobility

Health benefits constitute the project's most significant contribution, representing 84.2% of the total social wealth generated ($ 602.4 million USD over the horizon). Using the WHO'S HEAT framework (Table 1), the model projects avoiding 357 deaths associated with walking and 207 associated with cycling over a 15-year period.

The ACC encourages "first and last-mile" physical activity; in Manizales' steep terrain, users walk an average of 0.357 km to access stations. This confirms that mass transit in mountainous cities acts as a public health intervention, preventing non-communicable diseases such as hypertension and diabetes. The Relative Risk reduction (RRr) associated with the health benefits derived from physical activity are presented in the Table 1.

Table 1. WHO parameters and relative risk reduction calculation (Source: Own elaboration)

Mode of Transport	**Relative Risk (RR) (1)**	**Distance traveled year (km/person) D_{ref} (2)**	**Distance traveled year (km/person) D_{local} (3)**	**Relative Risk Reduction (RRr) (4) = (1 - RR) x (3) / (2)**	**Applicable Age Range**
Walking	0.89	771.7	233.9	3.3%	20 - 74
Bicycle	0.90	1213.3	233.9	1.9%	20 - 64

Social Cost-Benefit Analysis (SCBA) Summary

Table 2 summarizes the results of the SCBA over the 15-year horizon using the official Colombian Social Discount Rate (SDR) of 9.0%.

Table 2. Summary of social benefits of implementing the ACC (Source: Own elaboration)

Benefit Summary (15-Year Evaluation)		
Benefit Type	Monetary Benefit (USD)	% of Contribution by Benefit Type
Health	602403865	84.17%
Road Safety	46387233	6.48%
Accessibility	60953920	8.52%
CO2eq Emissions	5932546	0.83%
Totals	715677565	100.00%

Table 3. Calculation of the benefit-cost ratio (Source: Own elaboration)

Concept	Value (USD)	
Costs of implementation of the ACC	506398358.37	
Economic benefits received from the ACC	715677565.36	
Benefit-Cost Ratio (BCR)		1.41

The BCR of 1.41 (Table 3) indicates that for every peso invested, the society receives 1.41 pesos in return. This exceeds the 1.14 ratio previously reported for active mobility projects in Manizales (Cardona-Urrea et al., 2023), suggesting that the large-scale integration of the ACC network significantly amplifies social returns.

Table 4. Calculation of the economic net present value with different SDRs; Source: Own elaboration

SDR (%)	Economic Net Present Value (ENPV) (USD)
6	62832535.44
9	21951675.75
12	-6310125.44

The ENPV measures net social value at period zero, where positive values indicate social viability, zero indicates indifference, and negative values indicate unviability. Under Colombia's official 9% SDR, the project yields a positive ENPV of USD 21.95 million; at 6%, it increases to USD 62.83 million, while at 12% it becomes negative at USD -6.31 million (Table 4). This confirms that the project remains viable under moderate discounting but becomes sensitive when future benefits are heavily penalized. This pattern is consistent with the temporal profile of benefits, particularly health gains, which begin after year 5 and grow annually (World Health Organization, 2024).

Overall, the SCBA shows that social value is mainly driven by indirect externalities, led by health benefits of USD 602.4 million, followed by accessibility, road safety, and avoided CO_2-equivalent emissions.

Policy Recommendations for Local Governments

The findings support the formal incorporation of Social Cost-Benefit Analysis (SCBA) into transport planning for topographically constrained cities, particularly when evaluating Aerial Cable Car (ACC) systems. Under Colombia's official 9.0% Social Discount Rate, the Manizales ACC expansion yields a positive ENPV of USD 21.9 million over 15 years, with health benefits from active mobility representing 84.17% of total monetized benefits. This suggests that planning agencies in steep urban contexts should adopt the WHO HEAT methodology in ex ante appraisal to internalize the economic value of physical activity and avoided mortality. Given that project viability becomes negative at a 12% discount rate, differentiated discount-rate schemes should also be considered for long-term sustainable infrastructure.

Beyond appraisal, ACC systems should be planned as instruments of territorial equity, public health, and road safety. In Manizales, accessibility gains reach up to 19%, with Socioeconomic Stratum 3 accounting for 43.6% of the covered population and 46.6% of total time saved, showing that benefits are not limited to peripheral low-income areas. Therefore, local governments should integrate station catchment areas into Land Use Plans and Mobility Master Plans, coordinating pedestrian infrastructure, public space, social services, and road safety interventions within 10-minute walking isochrones.

In this sense, ACC systems should be framed not only as mobility solutions for complex topography, but as integrated policy tools for public health, decarbonization, and spatial justice.

CONCLUSION

The ex ante analysis confirms the socioeconomic viability of expanding the Aerial Cable Car (ACC) network in Manizales and Villamaría. Under Colombia's official 9.0% Social Discount Rate, established by Resolution 1092 of 2022, the project yields a positive ENPV of USD 21.9 million over 15 years and a BCR of 1.41, meaning that each USD invested generates 1.41 USD in social benefits. These results are consistent with regional evidence from systems such as "Mi Teleférico" in La Paz and exceed previous returns reported for isolated active mobility projects in Manizales.

Social profitability is driven by four monetized benefits. Public health is the largest component, accounting for 84.17% of total social value, with an estimated prevention of 357 deaths from walking and 207 from cycling over 15 years. Road safety benefits result from the ACC's segregated operation, which reduces conflict points between motorized traffic and vulnerable users, projecting a 32.1% reduction in fatalities and a 41.0% decrease in injuries within station catchment areas. Territorial accessibility improves through travel-time savings of up to 19%, with Socioeconomic Stratum 3 as the main beneficiary, representing 43.6% of the covered population and 46.6% of total time saved. Finally, environmental benefits include a 9.4% annual reduction in CO_2-equivalent emissions, avoiding 5865 tons of CO_2eq per year by shifting demand away from carbon-intensive motorized modes.

Although this research provides a robust socioeconomic framework for project appraisal, several limitations must be acknowledged. First, the multimodal accessibility model did not include the Public Collective Transport (TPC) network as an independent layer with routes, frequencies, waiting times, and transfers, although buses account for 32.4% of daily trips in Manizales. Therefore, the results reflect the ACC's potential as a sustainable backbone rather than full integration with the city's bus system. Second, the analysis relied on the 2017 Origin-Destination Matrix, the most recent official database available, which may not fully capture post-COVID changes in mobility patterns and travel demand. Third, the 15-year horizon assumes the operational consolidation of all projected lines, although the POT foresees phased implementation in the short, medium, and long term; this is relevant because several benefits, particularly health gains, require a five-year maturation period and gradual annual growth. Fourth, the 50.58% modal shift factor represents an idealized decarbonization scenario, while recent evidence from Line 3 suggests that ACC systems mainly attract bus users and pedestrians, with only marginal transfer from private vehicles and motorcycles, approximately 0.98%. This may reduce the expected CO_2eq and road safety benefits if private motorized trips are not effectively displaced. Finally, the SCBA does not include detailed costs of complementary social urbanism interventions around stations, such as lighting, tactile paving, public spaces, and pedestrian safety improvements, which are necessary to support the projected reduction in road fatalities and address persistent risks related to user behavior and improper infrastructure use.

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Abbreviations: ACC — Aerial Cable Car; ANSV — National Road Safety Agency (Colombia); BCR — Benefit-Cost Ratio; CF — Conversion Factor; CO_2eq — Carbon Dioxide Equivalent; ENPV — Economic Net Present Value;

HEAT — Health Economic Assessment Tool; OD — Origin-Destination; POT — Plan de Ordenamiento Territorial (Land Use Plan); RR — Relative Risk; RRr — Relative Risk Reduction; SCBA — Social Cost-Benefit Analysis;

SDR — Social Discount Rate; SVT — Social Value of Time; TAZ — Traffic Analysis Zone; TPC — Public Collective Transport; UPME — Unidad de Planeación Minero Energética (Mining and Energy Planning Unit); VSL — Value of Statistical Life; WHO — World Health Organization.

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