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Towards sustainable passenger transport: Carbon emission reduction scenarios for a medium-sized city

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ABSTRACT

The sustainability of transportation systems is frequently linked to human preferences, hence it is pertinent to align quotidian commuting choices with sustainable development goals. The main goal of the present research was to simulate eight scenarios designed to reduce the carbon dioxide emissions of passenger transport in a Colombian medium-sized city, taking into account the Global Warming Potential (GWP) of public and private vehicles, obtained by means of Life-Cycle Assessment (LCA). In this work we compared the environmental efficiency of the scenarios in order to make a contribution to the scientific discussion on sustainable mobility policies. Measures such as reducing the number of the most polluting vehicles, optimising the modal shares of public and private transportation systems, integrating electric vehicles, increasing the use of bicycles, and reducing mobility, have been tested. The results show that the current annual emissions from passenger transport in the selected city (263.98 kt CO_2-eq) could be decreased by up to 64.28% by implementing a 50% reduction in individual Trips per Day (TpD) and distances travelled by private and public vehicles. In addition, increasing the public bus fleet by 50% could yield a 56.92% reduction in the carbon dioxide released, while using an average occupancy of 30 passengers in buses could decrease the total emissions by 25.73%. Augmenting the occupancy ratio of private vehicles was shown to yield a 22.71% reduction in carbon dioxide released. Also, increasing the electric vehicle fleets by 50% can produce carbon emission reductions of 17.96% for the current energy mix and 20.08% for a 100% renewable energy mix; while boosting the use of bicycles and increasing the diesel car fleet yielded reductions of 9.24% and 5.06%, respectively. This article concludes that managing mobility and restricting commuting could be the most sustainable measure for life-cycle carbon emission reduction.

1. Introduction

The extremely rapid economic recovery the world has undergone since the Covid-19 vaccination process began, has generated a noticeable rebound of global CO_2-eq emissions from energy combustion and industrial processes. According to the International Energy Agency (2022), there was an increase of 6% in 2021 global carbon emissions when compared to the previous year, reaching 36,257 Mt CO_2-eq, of which 29.49% (10,693 Mt CO_2-eq) came from the combustion of oil-based fuel for energy and process purposes. If global greenhouse gases (GHG) emissions are taken into account, it is possible to affirm that 88.78% of those of 2021 correspond exclusively to CO_2. On this point, transport is the third sector with the highest reliance on fossil-based fuels, since it represents 24.23% of carbon dioxide emissions from all sectors, only exceeded by power and heat generation (40.82%) and combustion for industrial manufacturing and fuel production (25.43%) (Crippa et al., 2022). The remaining 9.52% correspond to building, industrial processes and agriculture.

The Intergovernmental Panel on Climate Change [IPCC] (2022) states that sustainable development will greatly depend on human behaviour and quotidian choices; since transport preferences should be

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Abbreviations

GWP	Global Warming Potential
LCA	Life-Cycle Assessment
GHG	Greenhouse Gases
ICE	Internal Combustion Engine
ADT	Average Distance Travelled
TpD	Trips per Day
TACE	Total Annual Carbon Emissions
EPD	Environmental Product Declaration
PCR	Product Category Rules
BEV	Battery Electric Vehicle
PM2.5	Particulate Matter ≤ 2.5 μm
ICEV	Internal Combustion Engine Vehicle

shifted to combine human health, global climate and sustainable development goals. It is estimated that around 55% of the cumulative reductions in the transit towards net zero global emissions are related to consumer choices in actions such as purchasing a vehicle. Behavioural changes such as replacing private vehicle commuting with cycling or public transportation will also provide an additional cumulative emissions reduction of 4% on the path to net zero (International Energy Agency, 2021).

Furthermore, if 20–50% of car trips are shifted to buses, and the remainder is replaced with cycling, walking or other means of public transport; the world could achieve a saving of 320 Mt CO2-eq by the mid-2030s, which underlines the importance of public transport systems in the urban net zero target (International Energy Agency, 2021). Within this framework, the sustainability of public transportation over the massive use of private vehicles has been illustrated in multiple urban areas. A case study carried out in Macau, China, was key in demonstrating that GHG emissions from light-duty gasoline cars and heavy-duty buses are 62.90 and 18.55 g CO_2-eq·pkm^{-1}, respectively. This means a potential reduction of up to 70.51% by increasing the use of buses, in strategies for mitigating Global Warming Potential (GWP) of the whole transport sector of a city, when compared to private automobiles (Song et al., 2018).

An overall reduction of 41% in total CO_2-eq emissions could be achieved in Hamburg, Germany, through the combination of shifting passenger car traffic to public transport usage and doubling bicycle traffic (Byrne et al., 2021). However, this study did not take into account resource losses during manufacturing, emissions from extraction processes, materials required for maintenance, or end-of-life impacts, as it only addressed materials and emissions from the production and usage of vehicles. Another study carried out in a medium-sized city of the United States showed a potential CO_2-eq emission reduction of 83.40% for Bus Rapid Transit with low emissions, which have a GWP of 41.05 g CO_2-eq·pkm^{-1}, while private vehicles release 247.24 g CO_2-eq·pkm^{-1} (Vincent and Jerram, 2018). In this case, a private mobility decrease (passenger-kilometres) of only 1.47% was simulated.

Table 1 shows that emission reductions of between 78% and 96.85% could be achieved by prioritising the use of public transport. Notwithstanding, buses have also been found to be one of the major contributors to carbon emissions from on-road vehicular sources when using conventional fuels. An impact inventory carried out in Manizales, a medium-sized city of Colombia, revealed that carbon dioxide was reported as the most abundant GHG linked to the transport sector, with a per-year total emission of 454 Gg that was predominated by passenger cars (42%) and diesel buses (26%) (González et al., 2017). Given that 100% of Manizales' buses are equipped with an Internal Combustion Engine (ICE), electrification of public transport should be implemented as a strategy for climate change mitigation, since it has been found to be key in achieving sustainable development goals 13 (climate action), 8 (economic growth), 7 (affordable and clean energy), and 3 (Good health and wellbeing) (Bhat and Farzaneh, 2022).

Table 1
Reduction of carbon emissions associated to the use of public transport.

Country	Compared vehicles	Public transport potential reduction	Findings related to public transport	Source
Qatar	Automobiles and a metro line.	78%	A metro line could reduce total emissions by 19.42 kt of CO_2-eq when compared with automobiles.	Al-Thawadi and Al-Ghamdi (2019)
Iran	Private car and auto-bus.	87.55%	Buses have a 94.57% lower contribution to CO_2-eq emissions of Teheran city, when comparing with private cars.	Kakouei et al. (2012)
Poland	Buses and passenger cars.	93.08%	Buses emit 93.09% less kg CO_2-eq when comparing with passenger cars.	Burchart-Korol and Folęga (2019)
Brazil	Subways, buses and cars.	96.85%	The underground of São Paulo and Rio de Janeiro emit 63.5 times less than cars and 8 times less than buses.	(Andrade and D'Agosto, 2019)

Public transport management in combination with other mobility measures for emission reduction has also been widely documented in the literature. Zhang et al. (2020) compared four scenarios to reduce the carbon released by the transport sector in a case study in China. Among the measures they assessed were (1) a combination of public transport management (increasing the number of public buses and underground trains) and switching the fuel from diesel to natural gas, (2) vehicle electrification and (3) a combination of both previous measures. The results show that the scenario involving a combination of public transport management and switching to natural gas fuel resulted in the highest reduction in carbon emissions (40.28%) but combining those measures with vehicle electrification is the optimal blend of policies to meet carbon emission targets in terms of cost-benefits.

Meanwhile, Yang et al. (2018) focused on travelling time as the main criteria to assess the potential emission reduction of replacing high-emission trips with trips using low-emission modes of transport. They found that low-emission trips have the potential to substitute high-emission trips to such a degree that the carbon emissions of Beijing could be reduced by up to 20%–25%, provided the low-emission mode trips take a maximum of 45 min longer than high-emission trips.

Nevertheless, there are no feasible scenarios found in the literature with comparative measures to reduce the CO_2-eq emissions of passenger transport from a life-cycle perspective. There is a gap of knowledge regarding the environmental benefits of the mobility strategies aimed at encouraging the use of non-fossil fuel-based means of transport and establishing a low-carbon passenger transport in a specific urban area. The potential emission reduction linked to the public transport systems is currently better reported, but sustainable scenarios regarding the population transported by vehicle type and the lifetime mileage of each transportation system have been less researched. Despite the importance of considering embodied energy to effectively address carbon emissions (Akizu-Gardoki et al., 2021), there is a lack of integration of a life-cycle perspective and, instead, direct exhaust fumes are what have mainly been taken into account.

The need to design locally-relevant policy measures for urban settings is what inspired our research question: what is the most effective policy measure to reduce the life-cycle carbon emissions from passenger transport in an urban setting? To address this issue, we tackled real parameters affecting the mobility and the environmental performance of the transportation systems in a medium-sized city. We hypothesised that increasing the modal share of public transport leads to the highest local emission reduction, taking into account the impacts of the vehicle's life-cycle. However, managing mobility and restricting commuting have been found to be the most sustainable measures for life-cycle carbon emission mitigation.

The present study makes a novel contribution to the reviewed literature by integrating parameters such as current population, modal share, local fleet size, vehicle occupancy, Trips per Day (TpD) and the Average Distance Travelled (ADT) of the vehicles; in order to compare the environmental performance of different mobility settings aimed at decarbonising the traffic and establishing the conditions to shift towards sustainable mobility in a medium-sized city. Thus, the main goal of the present research was to simulate eight scenarios designed to reduce Total Annual Carbon Emissions (TACE) (t CO_2-eq·day^{-1}) from passenger transport in Ibagué, Colombia, taking into account the GWP (g CO_2-eq·pkm^{-1}) of public and private vehicles, obtained by means of Life-Cycle Assessment (LCA). Flows such as battery replacements, charging point consumption and battery recycling supplies were included in the impact analysis of usage and final disposal of electric vehicles, in order to avoid underestimations in the modelling of specific low-carbon settings.

The study aimed to compare the environmental performance of the modelled measures with the current local situation. The proposed scenarios were designed by reducing the most polluting vehicles, improving the modal shares of public and private means of transport, and enhancing the use of electric vehicles and bicycles; with the purpose of providing valuable information to contribute to the quest for smart and sustainable cities and facilitate urban development, mobility management, transport system design and policy planning in future projects.

In this manuscript, the methodology chapter shows firstly how LCA has been integrated in order to have a comprehensive view of carbon emissions in each simulation. The chosen scenarios have also been described in this chapter. The results and discussion chapter shows the variations in TACE when integrating changes in the use of sustainable vehicles, renewable energies in the Colombian electricity mix, commuting patterns, and the city's public vehicle fleet. The conclusions chapter discusses considerations on the sustainability of the modelled measures when comparing these scenarios.

2. Methodology

To analyse the total carbon emissions from passenger transport in each proposed scenario, the GWP of private and public vehicles has been calculated through an LCA performed by using data on Ibagué's mobility. In this chapter, we first show the fleet size, the modal share, the ADT and the average of TpD by vehicle type. Then, the scope, the assumptions and the parameters considered in the GWP calculation are explained. The proposed scenarios to reduce the total carbon emissions of the selected medium-sized city are detailed in Section 2.4.

2.1. Target population and sample

Ibagué is a medium-sized Colombian city with a population of 536,087 citizens and a considerable local fleet of 217,671 vehicles, 774 of which are public buses (Centro de Información Municipal para la Planeación Participativa, 2021). The modal shares, population by means of transport and average TpD shown in Table 2 were estimated using data from Ibagué's Master Plan of Mobility and Public Space (Centro de Información Municipal para la Planeación Participativa, 2018). The fleet and ADT by private vehicles were obtained from Montoya et al. (2023), and that of regular buses were estimated using data from Consejo Nacional de Política Económica y Social (2020).

2.2. Scope and assumptions for Life-Cycle Assessment

Applying a life-cycle perspective to the proposal of new scenarios for traffic decarbonisation requires a structured framework for environmental impact assessment. Flow inventories allow for an accurate GWP estimation in all kinds of products, considering impacts from processes such as acquisition of raw materials, production, distribution, usage, maintenance and final disposal; as described in ISO 14044 (International Organization for Standardization, 2006). For this study we used the GWP of Ibagué's private vehicles, obtained in our previous research on life-cycle emissions related to passenger transport in urban and rural settings (Montoya et al., 2023). However, the GWP of the analysed electric vehicles was rectified by including battery replacements and charging point consumption upon modelling the use stage, and adding battery recycling supplies when modelling the final disposal stage. The current 82.98% renewable energy mix in the Colombian market for electricity (Supporting Information Table S3) was used for the impact assessment of the electric vehicles.

The per vehicle consumption of charging points was estimated by using the inventories for the construction and location of energy suppliers, obtained from the study performed by Lucas et al. (2012). These impacts were included in the LCA, taking into account the annual mileage of the motorcycles (Asociación Nacional de Empresarios de Colombia, 2019) and automobiles (Díaz Rondón, 2016) driven in Colombia. For the estimation of battery replacements, lifespans of 40,000 km (Carranza et al., 2022) and 150,000 km (Kannangara et al., 2021) were considered for e-scooter and e-car batteries, respectively. Table 3 gathers (1) the parameters used in our previous study for the analysis of the private vehicles and (2) the assumptions related to the public bus selected for the present research.

To address public transport in the proposal of low-carbon scenarios, we carried out an LCA for a low-entry diesel bus with a capacity of 340 hp and a weight of 11,000 kg, produced in Borås (Sweden). The established functional unit was g CO_2-eq per passenger-kilometre. The energy, products, supplies and transport used for the extraction of raw materials and for recycling processes at end-of-life were included in the analysis. In accordance with the data shown in Table 3, the distance from the production point to Ibagué includes trips by sea (SeaRates and

Table 2
Current situation of private and public mobility in Ibagué.

Vehicle	Fleet	Modal share	Population by vehicle type	ADT (km·trips^{-1})	Average of TpD (trps·day^{-1})
Petrol car	49,534	11.60%	61,673	9.64	2.01
Diesel car	392		488	9.64	2.01
Electric car	20		25	9.64	2.01
Conventional scooter	125,314	15.60%	83,619	8.72	1.09
Electric scooter	16		11	8.72	1.09
Electric bike	4888	1%	1250	6.20	0.39
Conventional bike	16,083		4111	6.20	0.39
Public buses	774	34%	182,269.57	9.15	1.71

Table 3
Characteristics of the private vehicles analysed.

Vehicle	Place of production	Distance for distribution	Lifetime mileage	Annual mileage	Average occupancy
Petrol car	South Korea	17,183 km	155,000 km	15,000 km	1.5 passengers
Electric car	South Korea	17,183 km	155,000 km	15,000 km	1.5 passengers
Diesel car	South Korea	17,183 km	155,000 km	15,000 km	1.5 passengers
Petrol motorcycle	Colombia	114 km	50,000 km	16,102 km	1.1 passengers
Electric motorcycle	China	19,149.47	50,000 km	16,102 km	1.1 passengers
Conventional bike	Colombia	203 km	15,000 km	1387 km	1 passenger
Electric bike	China	19,064 km	15,000 km	1387 km	1 passenger
Bus	Sweden	19,538.82 km	1,373,912 km	68,695.60 km	12 passengers

September, 2022) and trips by land to and from the sea ports (Legiscomex, 2022).

In the use stage, the selected bus has a lifetime performance of 1.65E07 pkm, which was estimated taking into account the average occupancy of the buses in Colombia (Universidadde Antioquia, 2020). The lifetime mileage was estimated by calculating a weighted average mileage per year, taking into account the annual distance travelled by the local bus fleet and the percentage shares of the Euro-compliant vehicles available (Rico Ospina, 2021). Also, a regulated lifetime of 20 years (Congreso de Colombia, 1993) was considered for this estimation.

The database behind the GWP calculation is Ecoinvent 3.8 (Ecoinvent, 2021). The LCA was performed in accordance with the Product Category Rules (PCR) 2016:04 for the assessment of the environmental performance of public and private passenger bus and coaches, developed by EPD International AB (2022c). Although no PCR for passenger cars is available, as they are still under development, this research addresses, as far as possible, the system boundaries and functional units for passenger road vehicles suggested in the aforementioned PCR.

2.3. Global Warming Potential calculation

This research followed the procedure established by ISO 14044 for LCA and performed the stages of goal and scope definition, inventory, impact assessment and interpretation on Ibagué's regular buses by

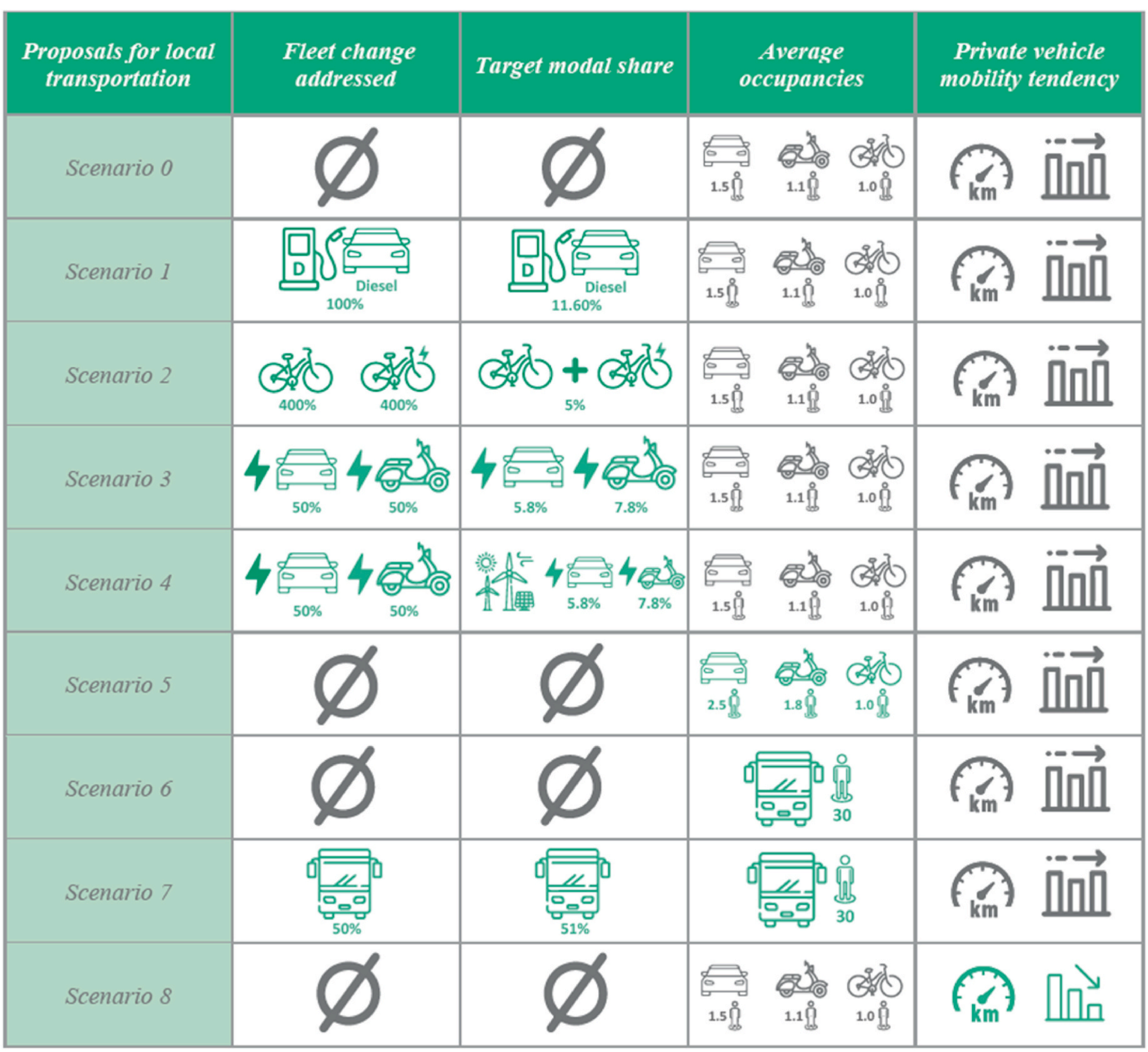

Fig. 1. Depiction of proposed scenarios.

means of OpenLCA (Supporting Information Table S1.). Data for modelling the distribution stage were obtained from importation data sheets published by Legiscomex (2022). The flows of the rest of the life-cycle stages were obtained directly from the Ecoinvent 3.8 database.

ReCiPe 2016 v.1.01 was used as the method for calculations, because of its Hierarchist perspective that provides a scientific framework for current technology development. According to Dekker et al. (2020), this is a widely used model for LCA since it offers an implementation of cause-effect pathways for the calculation of characterisation factors of substances and flows involved in the processes assessed. Midpoint was selected as the standardisation level for this method. It corresponds to a set of environmental impact indicators that allow us to express the significance of emissions with a low modelling uncertainty (Ismaeel, 2018).

2.4. Low-carbon scenarios proposal

In accordance with the methodology based on hypothetical sustainable scenarios proposed by Alejandre et al. (2022), the present research addressed eight settings designed to decarbonise traffic and improve environmental conditions related to commuting and passenger transport, by modelling measures such as increasing the usage of sustainable vehicles, decreasing mobility by shifting commuting patterns, and augmenting the city's public vehicle fleet.

Fig. 1 shows the desired modal shares related to the proposed fleet increments, in order to facilitate understanding of the hypothetical measures aimed at improving vehicle usage (Supporting Information Fig. S1). Each simulated scenario is described as follows:

- Scenario 1 is comprised of a 100% share of diesel cars in the fleet of private automobiles with an ICE, dispensing with Ibagué's petrol cars; which means that 11.60% of the city's population would be transported in diesel cars. The purpose of testing this measure is to analyse the pros and cons of diesel fuels in relation to global warming and air quality. It is known that diesel cars have an average reduction of 11% in life-cycle carbon emissions when compared to petrol cars (Montoya et al., 2023), but they also show 3.93% higher impacts than the latter in terms of terrestrial ecotoxicity (Puig-Samper Naranjo et al., 2021).
- Scenario 2 was designed by increasing the fleets of conventional and electric bikes by 400%, in order to achieve a bicycle modal share of 5% which falls below the 10% indicated by Fonseca et al. (2023) for starter cycling cities.
- Scenario 3 consists in increasing the share of Battery Electric Vehicles (BEV's) in the fleet of automobiles and motorcycles to 50%; which means that 5.80% and 7.80% of Ibagué's population would be transported in electric cars and e-scooters, respectively (Supporting Information Table S2).
- Scenario 4 is a complement to Scenario 3, with the same fleets but increasing the percentage of renewable energy in the Colombian electricity market from the current 82.98% (Supporting Information Table S3) to 100%. According to Zapata et al. (2023), this level of renewables dispatch may be attained in Colombia by 2030, unless delays in transmission construction take place, which could threaten outages in the country.
- Scenario 5 consists in using vehicles with average occupancies of 2.5 passengers for automobiles and 1.8 for motorcycles, instead of its current occupancies of 1.5 and 1.1. An average occupancy of 1 passenger for conventional and electric bicycles was assumed.
- Scenario 6 consists in assuming that Ibagué's public buses have an average occupancy of 30 passengers, which is the average nominal capacity of the most representative bus models in the city: the NQR bus (Centro Automotor Diesel, 2021a) and the NPR minibus (Centro Automotor Diesel, 2021b).
- Scenario 7 is a complement to Scenario 6, designed to increase the regular bus fleet by 50%, in order to augment public transport usage, with a 51% modal share.
- Scenario 8 consists in reducing the average TpD of private and public vehicles by 50%, and decreasing the ADT of private means of transport by 50% (Supporting Information Table S4). Conceptually, this strategy is aligned with reducing energy consumption while increasing the wellbeing of citizens (Akizu-Gardoki et al., 2018), and even illustrates how degrowth can have a positive impact (Akizu-Gardoki et al., 2020).

Table 4 shows the mean characteristics of each scenario proposed for the selected city, according to descriptions previously provided (Supporting Information Table S5).

The modal share of public buses needed for scenario 7 was calculated by estimating the additional demand for collective vehicles that would occur in the case of increasing the public transport fleet, as proposed. It was assumed that a percentage of the current population that uses private vehicles would be transported in public buses in this scenario. According to Centro de Información Municipal para la Planeación Participativa (2018), 28.2% of citizens use cars, motorcycles and bikes, with modal shares of 11.6%, 15.6% and 1%, respectively. In order to achieve the percentage increase needed for public transport in scenario 7, the modal shares of cars and motorcycles were reduced to 3.1% and 7.1%, respectively. The reduced percentages were assigned to public transport with the aim of reaching the required modal share.

With the purpose of ensuring sufficient vehicular capacity for the proposed modal share increases, passengers-per-vehicle indexes were calculated taking into account the current coverage of available transportation systems, in order to avoid the over- or under-utilisation of new fleets. The population transported in private vehicles from scenario 7 was calculated assuming the same percentage distribution of the current local fleet. The new fleets of private vehicles were estimated taking into account the transported population and the passengers-per-vehicle indexes (Table 5).

3. Results and discussion

A base-scenario with the current situation of carbon emissions in Ibagué has been established as the first set of results of this study, calculating the GWP of local regular buses by means of openLCA, in order to complement data obtained in the research carried out by Montoya et al. (2023), in which the CO_2-eq emissions per passenger-kilometre of private vehicles were given. As shown in Table 6, a regular bus emits 108.96 g CO_2-eq·pkm^{-1}, but the entire local fleet of buses is responsible for 113.22 kt CO_2-eq·year^{-1}.

The individual environmental performance of vehicles contrasts with that of fleet emissions, since a regular bus emits less carbon dioxide than petrol and diesel cars in terms of passenger-kilometre, but the local fleet of buses represents 42.90% of total emissions per day of the city. This is due to the high mobility of these vehicles, as they cover long distances with a high number of TpD: on average, 9.15 km travelled for each one of the 1.71 individual TpD. In total, 263.98 kt CO_2-eq are released by Ibagué's private and public vehicles every year and, for this study, these current conditions correspond to Scenario 0.

TACE can be reduced by 5.06% by dispensing with petrol cars and augmenting the fleet of diesel cars, as established in Scenario 1. This result suggests that diesel could be recommended over gasoline, when comparing fossil-based fuels used in medium-sized cities such as Ibagué. However, this setting presents the lowest reduction in carbon emissions and has a significant reliance on average occupancy and travelled distances, so diesel-based measures should be analysed taking into account the conditions of each region.

Despite conventional and electric bicycles being the most sustainable vehicles for commuting—inasmuch as they only emit 15.03 and 20.09 g CO_2-eq·pkm^{-1}, as shown in Table 6—the 5% modal share proposed for Scenario 2 generates a reduction of only 9.24% in TACE, hence this is the second setting with the lowest reduction of CO_2-eq, compared to the current local situation.

Table 4
Summary of the proposed low-carbon scenarios.

Proposed scenario	Changed characteristic	Petrol car	Diesel car	Electric car	Conventional scooter	Electric scooter	Electric bike	Conventional bike	Public buses
Scenario 1	Fleet (Vehicles)	0	49,926	20	125,314	16	4888	16,083	774
Scenario 2	Fleet (Vehicles)	40,994	324	17	109,248	14	24,440	80,415	774
Scenario 3	Fleet (Vehicles)	24,777	196	24,973	62,665	62,665	4888	16,083	774
Scenario 4	Renewable energy mix (%)	–	–	100%	–	100%	100%	–	–
Scenario 5	Average occupancy (Passengers)	2.5	2.5	2.5	1.8	1.8	1	1	12
Scenario 6	Average occupancy (Passengers)	1.5	1.5	1.5	1.1	1.1	1	1	30
Scenario 7	Fleet (Vehicles)	13,238	105	5	57,034	7	4888	16,083	1161
Scenario 8	ADT ($km \cdot trip^{-1}$)	4.82	4.82	4.82	4.36	4.36	3.10	3.10	9.15
	Average of TpD ($trps \cdot day^{-1}$)	1.01	1.01	1.01	0.55	0.55	0.20	0.20	0.85

Table 5
Data and procedure used for the fleet estimation of scenario 7 (Sc. 7).

Vehicle types and modal shares in Sc. 7	Vehicle	Passengers by vehicle type in Sc. 7	Vehicle shares by type in the current fleet	Passengers by vehicle in Sc. 7	Passengers per vehicle index	Vehicle fleet for Sc. 7
Automobiles (3.1%)	Petrol cars	16,619	99.18%	16,482	1.25	13,238
	Diesel cars		0.78%	130	1.25	105
	Electric cars		0.04%	7	1.25	5
Motorcycles (7.1%)	Conv. Scooter	38,062	99.99%	38,057	0.67	57,034
	Electric scooter		0.01%	5	0.67	7
Bicycles (1%)	Electric bike	5361	23.31%	1250	0.26	4888
	Conv. Bike		76.69%	4111	0.26	16,083
Collective (51%)	Buses	273,404	100%	273,404	235.49	1161

Table 6
CO_2-eq emissions from the transportation systems of Ibagué.

Vehicle type	Vehicle	Global Warming Potential g CO_2-eq·pkm^{-1}	Total annual emissions kt CO_2-eq·$year^{-1}$
Automobiles	Petrol car	277.02	120.81
	Diesel car	246.38	0.85
	Electric car	104.32	0.02
Motorcycles	Conventional scooter	100.01	29.00
	Electric scooter	34.24	0.00
Bicycles	Electric bike	20.90	0.02
	Conventional bike	15.03	0.05
Collective	Bus	108.96	113.22
Total			263.98

The carbon emissions of Ibagué could be decreased by 17.96% if half the cars and motorcycles used in that city were electric, as proposed for Scenario 3. An additional reduction of 2.11% can be achieved if a 100% renewable energy mix is used in the Colombian market for electricity, reaching 210.97 kt CO_2-eq per year, according to results from the simulation of Scenario 4. Meanwhile, if policies and mobility measures could increase the average occupancies of cars and motorcycles to 2.5 and 1.8, as proposed for Scenario 5, the TACE would be further reduced, reaching 204.03 kt CO_2-eq.

Modelling scenario 5 required a new fleet size estimation, because it was assumed that an increase in average occupancies would imply a decrease in circulating vehicles. This estimation was made by extrapolating the current number of passengers per vehicle with the aim of getting a local average of citizens by transportation system while also considering the current passenger flow in the simulation process. New fleet sizes were calculated by dividing the average number of transported citizens by the proposed average occupancies.

With regard to the results of the Scenario 6 simulation, 196.04 kt CO_2-eq would be released annually in Ibagué, instead of the current 263.98 kt CO_2-eq, if the average occupancy of public buses were increased from the current 12 passengers to 30. These emissions could reach 113.73 kt CO_2-eq if the bus fleet were augmented by 50%, which would require a 51% modal share of public transport, as proposed for Scenario 7. In this setting, an index of 235.49 passengers per bus was used in order to ensure the availability of vehicles in the selected city.

A total emission of 94.30 kt CO_2-eq·day^{-1} is reached if the mobility of Ibagué is restricted by reducing the average number of individual TpD in private and public vehicles by 50%, and decreasing the ADT of private means of transport in the same proportion, as proposed for Scenario 8. These measures could require strategies such as promoting home-working in order to discourage commuting. However, it is pertinent to consider that a trade-off effect between work and non-work trips may influence the carbon footprints of home-based workers (Cerqueira et al., 2020). As can be seen in Fig. 2, this scenario is the most sustainable of all the simulated settings. It must be clarified that the scenarios could be also combined with each other to increase reduction efficiency.

Each simulated scenario offers a considerable reduction of total carbon emissions from passenger transport in Ibagué; assuming accurate fleet sizes, occupancy ratios and vehicular displacements in each setting. However, even if significant efforts were made to reduce private vehicle mobility as needed for Scenario 8, it is pertinent to consider the particular conditions of the public transport system in the target of reducing a city's CO_2-eq emissions. Fig. 3 provides a comparison of reductions offered by each scenario.

The results obtained in the simulation of scenarios 6 and 7 contrast with the findings of previous research showing potential emission reductions related to the use of public transport. According to the information gathered in Table 1, buses have the potential of decreasing the carbon emissions of Teheran (Iran) by 87.55% when compared to automobiles (Kakouei et al., 2012). This contrasts with the reduction obtained in Scenario 6, which shows that increasing the use of buses by

Fig. 2. Comparison of carbon emissions in the proposed scenarios.

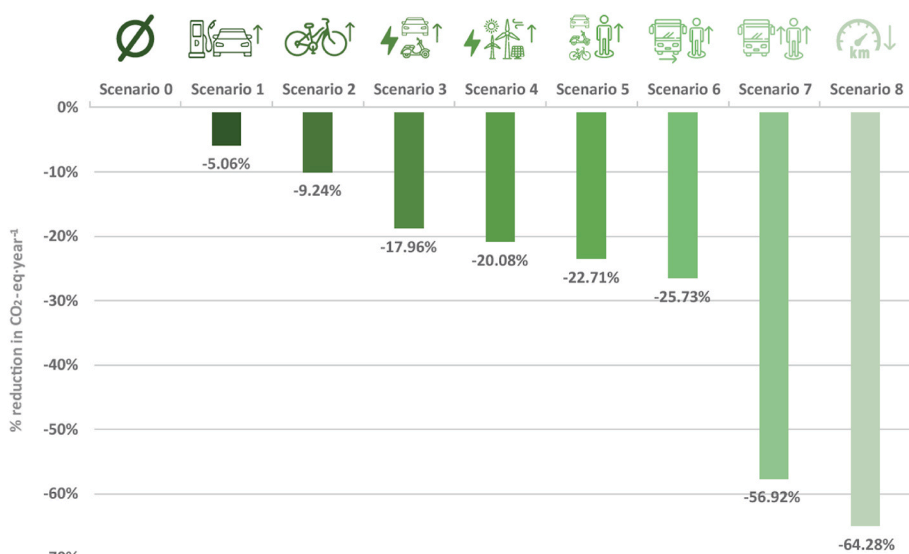

Fig. 3. Comparison of carbon emission reductions in the proposed scenarios.

encouraging a higher average occupancy allows a reduction of only 25.73%. Even if the bus fleet were augmented by 50%, as in Scenario 7, the reduction would reach 56.92%, which is considerably lower than that shown in the aforementioned study.

Meanwhile, emission reductions of 93.08% (Burchart-Korol and Folęga, 2019) and 96.85% (Andrade and D'Agosto, 2019) have been reported when comparing the environmental impacts of buses and cars in case studies performed in Poland and Brazil. Nevertheless, these studies did not compare specific scenarios with detailed measures and precise assumptions to estimate the improvement in the environmental effectiveness of public transport-based strategies.

Our study has hypothesised a more realistic increase in public transport, not so far as to replace all the private vehicles, but by augmenting the use of regular buses to 51%, so that policy makers can begin the shift to sustainable transportation within current social and economic constraints. Within this framework, the Environmental Product Declaration (EPD) of the Irizar electric bus shows a GWP of 8.19 g CO_2-eq·pkm^{-1} according to EPD International AB (2022a), while the EPD for the Solaris Urbino 18 electric bus shows an emission of only 11 g CO_2-eq·pkm^{-1} (EPD International AB, 2022b). This underlines the potential of electric buses to reduce the life-cycle impacts of passenger transport in urban settings, hence it is pertinent to design appropriate scenarios exploring the electrification of public transport, taking into account the specific conditions of occupancy ratio and modal share of collective vehicles in future research.

In this study we have shown the conditions required to achieve a feasible carbon emission reduction by enhancing the use of public transport, so as to improve mobility in the selected city. We have also considered the impact of the ADT on the GWP of regular buses, which was calculated by integrating the real data of local public transport into the LCA.

As Fig. 4 shows, our approach sheds light on how an increased bus

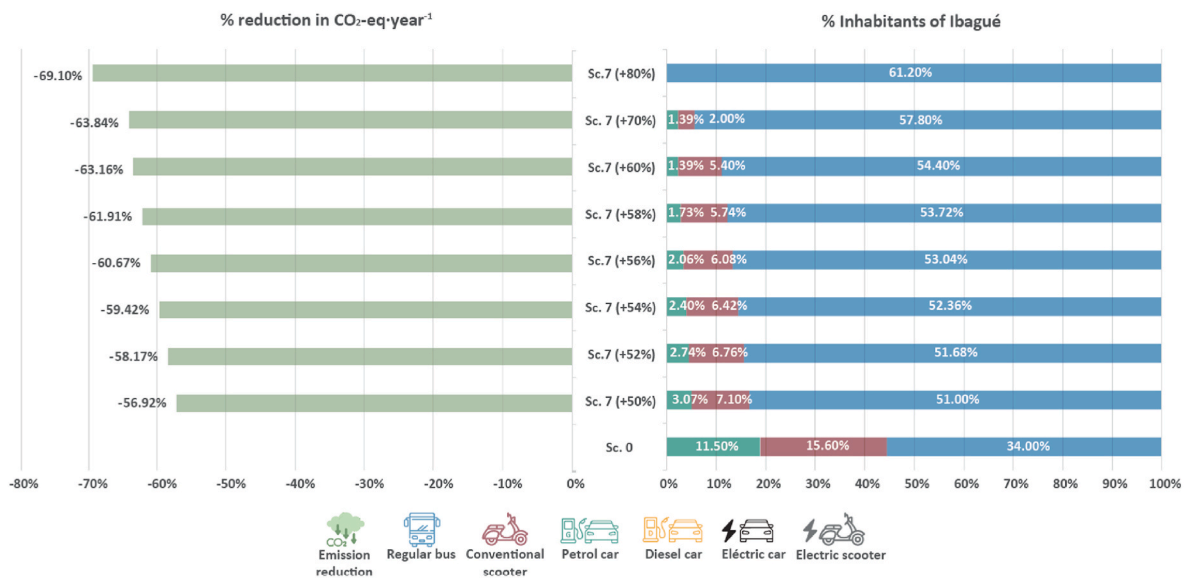

Fig. 4. Emission reductions of Scenario 7 with several fleet increases.

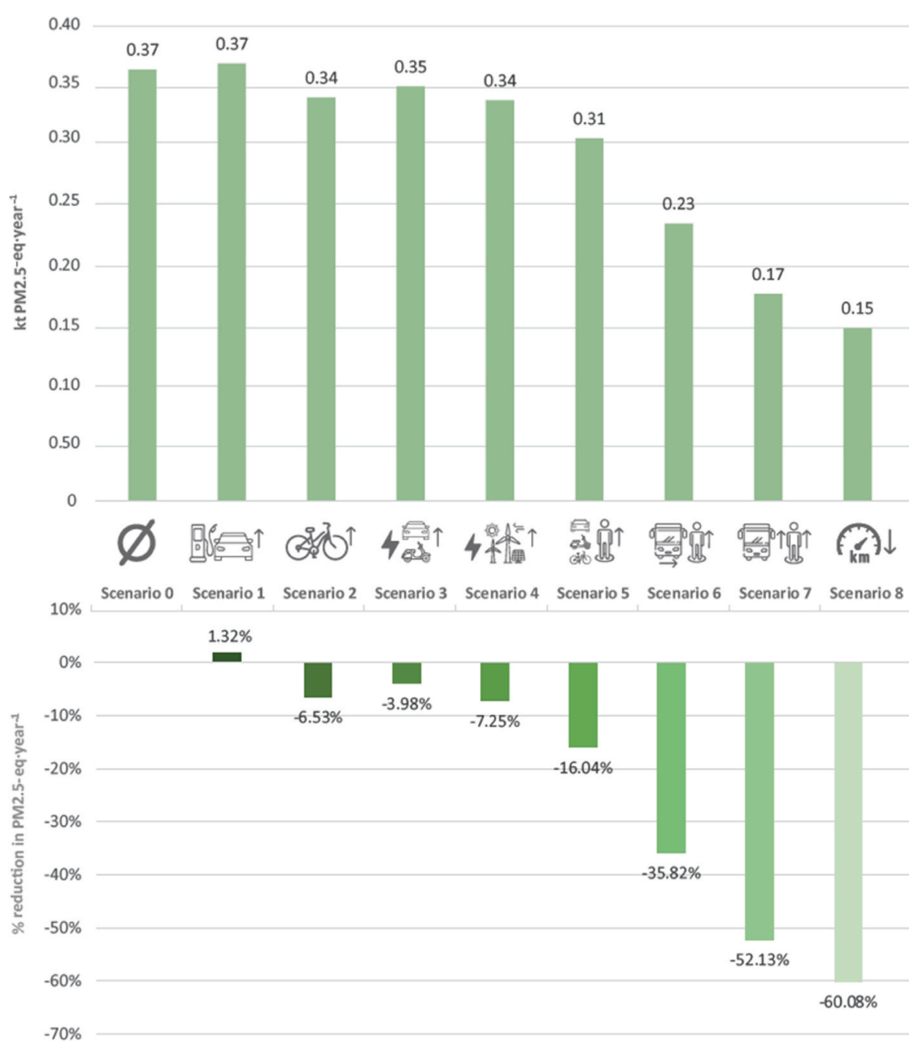

Fig. 5. Comparison of emissions of PM2.5 in the simulated scenarios.

fleet has an influence on the reduction of life-cycle carbon emissions from passenger transport in a medium-sized city. By changing the conditions of Scenario 7, it was possible to show that emission reduction can be optimised (achieving a range from 56.92% to 69.10%) as the local bus fleet is gradually augmented by up to 80%. Nonetheless, policy designers should address vehicular crowdedness as a key concern for potential users, since this is the most significant barrier to the use of regular buses, according to Suman et al. (2018). Mobility strategies could be required in order to avoid a growth in private commuting motivated by passenger discomfort on public transport.

To achieve a 70% increase in the fleet of regular buses, it is necessary to reach a public transport modal share of 57.8%; which means that the modal shares of automobiles and motorcycles must be decreased to 1.39% and 2%, respectively. It was assumed that all passengers currently transported by car and motorcycle would commute on regular buses, in order to achieve a 61.2% modal share of public transport, as needed to obtain an 80% increase in the fleet of regular buses (Supporting Information Table S6). Taking into account the fact that reducing the population currently transported on foot (25.9%), by bicycle (1%) and in non-determined vehicles (11.9%) is not environmentally ideal, it is possible to affirm that increasing the bus fleet by more than 70% is unrealistic, although it might be desirable for local administrators and policy designers.

With the aim of testing the environmental performance of the designed scenarios in terms of air quality and energy consumption, we have also assessed the particulate matter formation and cumulative energy demand related to the analysed vehicles in order to simulate each scenario regarding these impact categories. The results were expressed in terms of kilotons of ≤ 2.5 μm particles (PM2.5) emitted annually and terajoules of total energy content per year, respectively.

The results of Scenario 1 are striking when analysing particulate matter formation: using 100% diesel cars actually increases PM2.5 emissions by 1.32% when compared to the base scenario, which contrasts with the 5.06% diminution observed in terms of GWP. Also, increasing the bicycle modal share could be more efficient than augmenting the fleets of electric vehicles and keeping the current Colombian energy mix, since Scenario 3 offers a 2.55% lower reduction of particulate matter emissions than Scenario 2.

Despite the fact that the use of diesel cars is associated with increasing PM2.5 emissions, as shown in Fig. 5, it can also yield a higher reduction of cumulative energy demand when compared with the increase in the bicycle modal share proposed in Scenario 2, as depicted in Fig. 6. Nonetheless, this scenario includes an augmented fleet of electric bikes run with the current Colombian energy mix, which may diminish the environmental benefits of cycling in terms of total energy content. Thus, ensuring a 100% renewable energy mix is appropriate so as to boost the use of electric vehicles and enhance the bicycle modal share in a mid-sized city.

Fig. 6. Comparison of cumulative energy demand in the simulated scenarios.

It has been detected that a scaled-up investment is needed to support the infrastructure required to advance in sustainable passenger transport in urban settings. Mobilising private investment has been found to be necessary to meet the economic needs, and the increasing pressure on public finances has encouraged governments to increase private sector participation in land transport infrastructure, whether through public-private partnerships or full privatisation (Ang and Marchal, 2013). Within this context, future research could explore how public entities can boost the adoption of alternative technologies to complement mobility electrification, such as autonomous vehicles. To this end, two courses of action could be explored: (1) encouraging the contribution of key stakeholders through platforms that facilitate the sharing of public data for mobility solutions providers and road users; and (2) by supporting road tests for autonomous vehicles, which are expected to clarify business opportunities and incentivise the leading global tech and automotive players to test and deploy their innovative projects in a given region (Camps-Aragó et al., 2022).

Regarding the adoption of active passenger transport as a strategy for sustainable mobility, policymakers could encourage walking and cycling by creating more pedestrian-friendly streets, which have been found to be effective in reducing greenhouse gas emissions and improving public health, since they increase physical activity, as shown in a study on sustainable transportation planning in urban areas carried out by Patil (2022). This research also showed that making public transportation more accessible could encourage people to use it, while also providing affordable transportation options for low-income communities. In addition, boosting the use of electric vehicles was found to be advantageous given the lower operating costs, reduced noise pollution, and the improved performance electric vehicles have, in accordance with the aforementioned study.

Another measure that could be explored in the near future is to charge drivers a fee to enter congested areas. In addition to improving air quality, this strategy may reduce the demand for fuel, leading to lower prices and reduced transportation costs for consumers (Patil, 2022). Within the costs associated with this measure are the installation of tolling equipment and the hiring of additional staff, but the long-term benefits of reduced traffic congestion and improved public transportation options can help to offset these costs (Patil, 2022).

It is important to note that policymakers may encounter several trade-offs when considering different strategies to boost sustainable transport options. For instance, measures such as sharing schemes appear to attract users who would otherwise have walked or used public transport (European Environment Agency, 2020). In this regard, the environmental trade-offs related to public transport, walking and cycling should be explored in future studies, given the importance of these modes of transport in improving public health and reducing GHG emissions (Rojas-Rueda et al., 2012).

In summary, urban planners could prioritise a restriction in the mobility of private vehicles as a strategy to reduce carbon emissions in medium-sized cities. To this end, economic efforts can be focused on assessing the feasibility of increasing homeworking without negatively affecting industry productivity and the private sector. Future research could tackle the social cost and economic impact associated to a reduction of commuting, given that our approach only took into account the environmental aspects of the measures tested. The present study did not assess the potential trade-offs that may arise when promoting homeworking, so policy makers and researchers should consider factors such as infrastructure, technical capacity and financial resources required to implement this strategy.

Our findings can be also considered in making policy decisions aimed at establishing a low-carbon mobility, taking into account the modal shares of public and private vehicles. Nonetheless, active modes of transport should be analysed in the context of medium and small-sized cities, where commuting distances may be shorter than those in larger cities. In this research we addressed the GWP of bicycles, but future studies could explore in further depth other active modes such as walking. Finally, boosting the use of public transport is necessary to consider current social and economic constraints while reducing carbon emissions, as we demonstrated by analysing the regular buses of Ibagué. However, a scenario that includes electric buses with different modal shares could be tested in future research, in order to examine the feasibility of the electrification of public transport in urban settings.

4. Conclusions

The private mobility of Ibagué accounts for 99.61% of the available transportation systems, including conventional and electric vehicles. For this reason, a 50% reduction in displacements and distances travelled by private vehicles, combined with a 50% decrease in individual trips made by bus, could save up to 64.28% of the current carbon emissions from passenger transport in the city. We can conclude that a mobility restriction on private means of transport could be the most effective measure in the effort to mitigate GWP and achieving low-carbon scenarios in medium-sized cities. Strategies such as those proposed in Scenario 8 can be emphatically recommended, since the simulation results showed that they perform even better than public transport-based measures.

Despite the fact that public transport sustainability has already been demonstrated in several pieces of research, the present study allowed us to establish specific conditions to achieve a functional low-carbon scenario based on regular buses. It was shown that a modal share increase of public transport in a medium-sized city should be promoted, following an accurate analysis based on precise data about vehicular capacities and fleet sizes. It was shown that promoting public transport usage by augmenting available buses could be an effective measure, taking into account that average occupancy should be increased to 30 passengers in order to reach a 56.92% reduction in daily carbon emissions, in the particular case of Ibagué.

The Scenario 6 simulation, which only addressed the average occupancy of regular buses, yielded a reduction of only 25.73% in daily carbon emissions, hence it is fair to state that a bus-based reduction scenario should be focused not only on occupancy ratio but also on fleet size. At all events, a public transport modal share growth should be considered in order to obtain environmental benefits from public vehicles. A significant diminution in private mobility can be achieved by ensuring the appropriate conditions in a city's public transport system, with the aim of motivating the use of regular buses for commuting. In this study, car and motorcycle modal shares were reduced by 8.5% each, in order to reach the 51% modal share needed for public transport in Scenario 7.

A specific situational analysis of public transport could be recommended to local administrators, in order to allow for the conditions that may interfere in social behaviour and mobility preferences. If the fleet sizes shown in Table 2 are considered, it is possible to affirm that 88.94% of available vehicles correspond to private transportation systems with conventional ICE. Therefore, Ibagué has an important reliance on fuel-based means of transport. Therefore, the feasibility of a strategic public transport system should be measured, taking into account that the strategies designed for Scenario 7 could be effective in significantly mitigating the total carbon emissions of the city.

The approaches described are not mutually exclusive: efforts could be made to promote both walking and the use of public transport as alternatives to replace private vehicle trips in a city. Discouraging the use of cars and motorcycles could increase the modal share of public transport while reducing general mobility, meaning that a city could obtain the environmental benefits observed in Scenarios 6, 7 and 8.

Despite the sustainability of electric vehicles, especially if renewable energy is used, augmenting occupancy ratios of Internal Combustion Engine Vehicles (ICEV) is recommended over promoting an increase of BEV's as proposed for scenarios 3 and 4; taking into account that using average occupancies of 2.5 passengers in automobiles and 1.8 in motorcycles could reduce TACE by 22.71% versus the 20.08% reduction obtained with a 100% renewable energy mix and a larger fleet of electric vehicles. As an advantage, this setting does not require a direct economic investment in vehicular capacity or fleet coverage.

Regardless of the low reductions in CO_2-eq emissions shown in Fig. 3 for Scenarios 1 and 2, the measures proposed in these settings should not be ruled out. If vehicular electrification were not feasible, a medium-sized city could discourage the use of petrol cars in favour of diesel cars, considering the results of the Scenario 1 simulation. At the same time, bicycles should be considered for the target of achieving optimised GHG levels, since this is the most sustainable vehicle for private transportation, as previously shown.

In this work, we hypothesised that increasing the modal share of public transport would lead to the highest local emission reduction. However, our findings indicate that managing mobility and restricting commuting are the most sustainable measures for life-cycle carbon emission mitigation. Within the lessons gleamed from this work, it can be seen that policymakers should assess the environmental benefits of sustainable mobility strategies from a life-cycle perspective instead of taking into account only direct exhaust fumes or the operational impacts of vehicles. Furthermore, urban planners need to consider other impact categories in addition to GWP, since we have detected that the strategies involving diesel or electric vehicles can be counterproductive when analysed in terms of cumulative energy demand or particulate matter formation. These results are expected, to a large extent, to pave the way towards sustainable passenger transport.

CRediT authorship contribution statement

Jacid Montoya-Torres: Investigation, Writing – original draft. **Ortzi Akizu-Gardoki:** Validation, Supervision, Writing – review & editing. **Carlos Alejandre:** Formal analysis, Investigation, Writing – original draft. **Maider Iturriondobeita:** Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138149.

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