The pathway to sustainable passenger transport: a life cycle perspective of decarbonisation strategies

Jacid Montoya-Torres

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PhD Thesis in Project Engineering

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By

Jacid Montoya-Torres

Directed by Maider Iturrondobeitia and Ortzi Akizu-Gardoki

Bilbao, September 23, 2023

PhD Thesis in the Doctoral Programme in Project Engineering

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Dissertation submitted to the University of the Basque Country (UPV/EHU) as fulfilment of the requirements for the PhD degree in Project Engineering

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To my wife Monica Alejandra Manjarrés, who has unconditionally supported every dream and has been part of every success. To my parents, Jacid Montoya Varon and Martha Lucía Torres Vera, who raised me with the conviction to pursue every dream I have dreamed. To my brothers Jeisson Steven Vera, Crhistian Alejandro Vera and my whole family Montoya, Varon and Torres. Special thanks to Maider Iturrondobeitia, Ortzi Akizu Gardoki, Rikardo Minguez Gabiña and the University of the Basque Country for the support and guidance. Lastly, to the most important... The Creator and Father of all.

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1. Abstract

1. Abstract

The mobility global demand is expected to grow while transportation emissions must decrease in order to prevent a significant global temperature rise in the near future. In this sense, Life Cycle Assessment (LCA) has been found to be necessary to improve decision-making and establish efficient strategies for the new challenges related to the carbon footprints of the current automotive industry and the environmental impacts of passenger transport. Thus, the main research goal of the present doctoral thesis has been to estimate the life-cycle environmental impacts of private and public passenger vehicles, with the purpose of analysing potential strategies to reduce their Global Warming Potential (GWP) and shift to a sustainable passenger transport in urban contexts.

For such purpose, three main contributions have been made in the form of scientific articles, in addition to a conference article as a fourth contribution. In order to quantify vehicle carbon footprints by means of LCA and simulate feasible scenarios to explore the potential of public transport, use of bicycles, vehicle electrification and mobility restriction in reducing carbon emissions, the following parameters were addressed in the structure of the Doctoral Thesis:

- Average occupancy
- Fleet size
- Annual mileage
- Lifespan
- Average distance travelled
- Type of propulsion technology
- Vehicle type

The environmentally optimal time in which to replace private vehicles has been also explored in this PhD Thesis, with the aim of establishing potential pathways to address the benefits of strategies based on vehicle substitution such as scrappage schemes, in the target of reducing life-cycle carbon emissions in urban contexts.

In the first place, to clarify the differences between urban and rural settings when estimating the Global Warming Potential of private vehicles, comparative LCA were performed in two case studies in Latin America. The first set of results showed that, on average, emissions from the analysed urban area are 23% higher than those of the rural case study. It could be concluded that, if the average travelled distance and number of per-day trips are taken into account, great differences are striking: for the urban area, the average daily emissions per passenger is 120% higher than that of the rural area.

Having observed that the emissions from passenger transport in urban areas need to be reduced, this work simulated eight scenarios which were designed to reduce the carbon dioxide released by private and public vehicles in medium-sized city. Measures tested include reducing the number of the most polluting vehicles, increasing the use of bicycles, integrating electric vehicles, optimising the modal shares of private and public vehicles and reducing mobility.

In this case study, the results showed that the current annual emissions from passenger transport in the selected city could be decreased by up to 64.28% by implementing a 50% reduction in individual trips per day 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. Bearing these outcomes in mind, it was concluded that managing mobility and restricting commuting could be the most sustainable measure for life-cycle carbon emission reduction.

Finally, to explore potential pathways to address the benefits of strategies based on vehicle substitution, the environmentally optimal time in which to replace a petrol car has been established, by simulating five substitution scenarios that include a newer version of this car, a diesel car and an electric car. The average occupancy, annual mileage and the energy mix on the market for electricity were addressed in this approach. The Greenhouse Gas (GHG) emissions from the selected vehicles were quantified, with the aim of determining the optimal number of years after which substitution should take place.

The results of this part of the research showed that an old petrol car can be efficiently replaced after 8.88 years if an electric car is selected as the substitute. However, this period would decrease to 6.55 years if the new vehicle were powered with 100% renewable energy. Moreover, an environmentally optimal replacement could be made at 3.29 years, if the substitute were an electric car run with an average occupancy of 3 passengers and a 100% renewable energy mix. It was also demonstrated that the EURO 5 diesel car could be a replacement option for the base vehicle after 13.65 years, considering GWP impacts exclusively.

By contrast, there were no environmental benefits detected for using diesel cars when considering PM2.5 emissions, hence they are not a feasible environmentally optimal substitution looking at this impact category. Also, it could be concluded that the substitution could be up to 69.94 % sooner if a cleaner energy mix is used to run the replacement car, which underlines the importance of addressing the specific conditions of electricity market and use patterns when implementing measures such as scrappage schemes.

In this doctoral thesis, has been argued that locally relevant policy measures that intend to mitigate global warming and reduce carbon emissions of passenger transport should consider key factors including social behaviour, commuting patterns and prioritised environmental impacts. Also, accessibility to public transport, energy mix in the electricity market and cost-benefit considerations on vehicle electrification are needed to be addressed for the purpose of transiting to low-carbon scenarios in the city.

2. Graphical abstract

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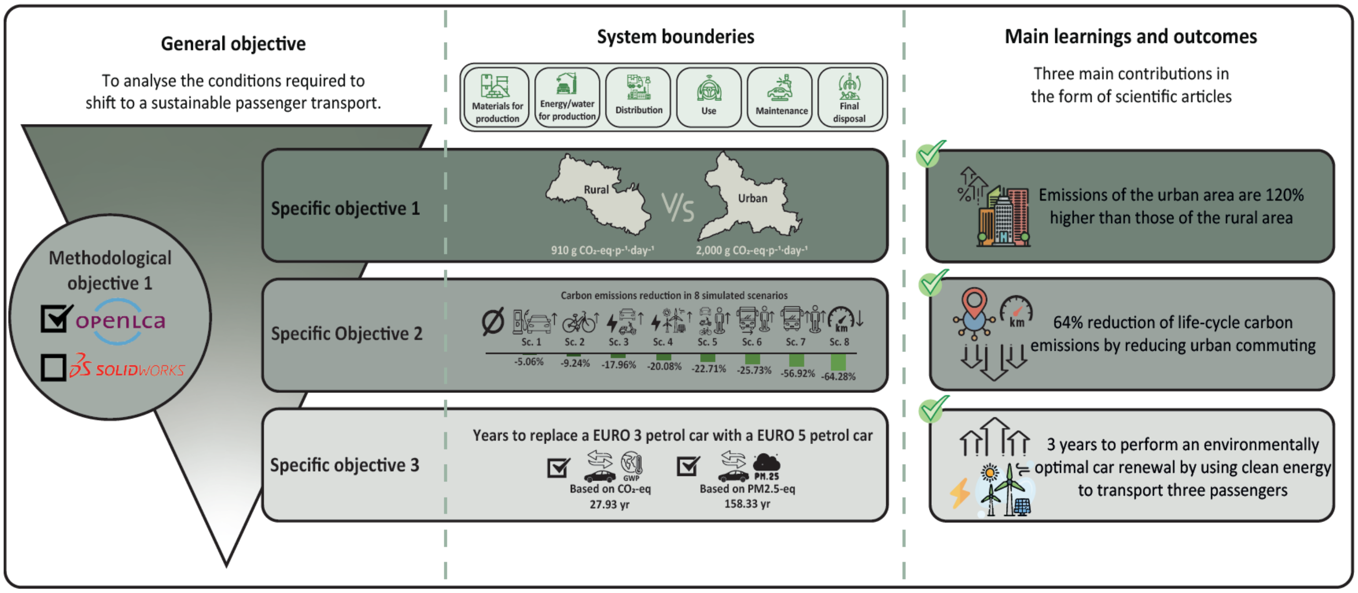

Figure 1. Graphical abstract of the Doctoral Thesis.

3. Introduction

3. Introduction

The Paris Agreement adopted in 2015 established the goal of mitigating the increase of the world's average temperature, by keeping it below 2°C compared to pre-industrial levels, which requires achieving carbon neutrality by 2050: in accordance with Caiardi et al. (2023), the strategies needed to such purpose would benefit from the application of perspectives based on Life Cycle Assessment (LCA), a recognized method for the environmental assessment of products that takes into account the impacts associated with the entire life cycle. These perspectives could allow to (1) extend the carbon dimension to a broader and multi-criteria environmental dimension, and (2) consider the entire life cycle rather than just emissions from each territory.

The World Economic Forum (World Economic Forum, 2021) states that to prevent a global temperature rise of more than 1.5 ºC by 2030, transportation emissions must decrease by 50% while mobility demand is expected to grow by 70% in the same period. According to Folęga & Burchart-Korol (2017), LCA has also been found to be necessary to improve decision-making and establish efficient strategies for the new challenges related to the carbon footprints of the current automotive industry and the environmental impacts of passenger transport.

At this point, the main research goal of the present Doctoral Thesis has been to estimate the life-cycle environmental impacts of private and public passenger vehicles, with the purpose of analysing potential strategies to reduce their Global Warming Potential (GWP) in the context of urban transport. Parameters such as average occupancy, fleet size, annual mileage, lifespan and average distance travelled have been taken into account in order to simulate feasible scenarios and explore the potential of public transport and vehicle electrification in reducing carbon emissions. The environmentally optimal time in which to replace private vehicles has been also explored with the aim of establishing potential pathways to address the benefits of strategies based on vehicle substitution, in the target of reducing life-cycle carbon emissions.

The following literature review will examine the main findings of previous research on LCA applied to urban and rural transportation systems. As it has been found, there is a scientific consensus on the importance of electric vehicles and public transportation in decarbonising passenger transport, given their potential to reduce environmental impacts in urban settings. It has also been shown that strategies focused on replacing high-emission vehicles do not offer significant environmental benefits, as scrappage schemes have been considered inefficient due to their cost. Nonetheless, the studies reviewed have an important drawback in that they do not consider the life-cycle impacts of the analysed vehicles, which is a gap addressed in the present doctoral thesis, as can be seen in sections 3.1, 3.2 and 3.3.

3.1 Life Cycle Assessment applied to passenger transport

In 2019, the global Greenhouse Gas (GHG) emissions reached the amount of 59 gigatons of carbon dioxide equivalent (Gt CO2-eq) of which 15% came from transport. The land modes of transport have the third highest average annual emissions growth with a 10% contribution to global GHG (Intergovernmental Panel on Climate Change [IPCC], 2022). This sector has the responsibility of contributing to the achievement of the sustainable development goals by avoiding the consumption of fossil fuels and regulating the use of more environmentally-convenient transport services for each area.

To contain the increment of climate disasters, several countries have been replicating the goals of global warming mitigation at all levels, applying them to regions and cities by means of policy measures adapted to each territory. For instance, the European Union has set an objective of reducing by 55% its GHG emissions by 2030 and achieving carbon neutrality in 2050 (Dorr et al., 2022). Policies such as the Kyoto Protocol and the Paris Agreement have been designed to reduce GHG emissions, promoting energy decarbonisation and transport electrification (Kazancoglu et al., 2021). For such purpose, vehicle emissions should be estimated and compared, as a first step in the analysis of the current road transport situation in each geographical area.

Multiple approaches have been adopted to measure the carbon emissions from passenger vehicles. Tiseo (2021) compared the carbon footprints of selected vehicles such as automobiles, motorcycles and bicycles, by analysing worldwide data on travelled kilometres per passenger transported. The study found that, while a petrol car emits 192 grams of carbon dioxide equivalent per passenger-kilometre (g CO_2-eq·pkm^{-1}), the carbon footprint of a motorcycle is 46.4% lower: 103 g CO_2-eq·pkm^{-1}. However, this kind of study omits the emissions from stages such as the vehicle's production or end-of-life, which underlines the relevance of applying a life-cycle perspective when comparing CO_2 emissions from fuel-based means of transport, including four- and two-wheel vehicles.

LCA has been widely used to evaluate the environmental efficiency of vehicles from a more comprehensive perspective. Nevertheless, some factors could affect the calculation of carbon emissions of vehicles e.g., system boundaries, functional units, vehicle type and, especially, the geographical differences in the power structure, ambient temperature, and driving conditions (Xia et al., 2022). Thus, generating useful information for urban mobility planning and policy design requires including as many vehicle categories as possible when making a life-cycle impacts comparison, taking into account propulsion systems based on diesel, gasoline and electricity for two- and four-wheel vehicles.

Reviewing the literature to obtain data on carbon footprints for making policy decisions associated with passenger transport, has a significant drawback in that previous studies address specific means of transport with no comparative analysis related to a particular region. A consistent comparison of vehicle GHG emissions results found in reviewed literature requires an accurate harmonisation to avoid assumptions which may vary significantly across time and different geographies (Raugei, 2022). In this respect, it has been detected a gap of knowledge regarding the impacts related to the usage of private vehicles linked to a certain region and the respective characteristics of its private vehicle fleet, as they have been addressed in the present doctoral thesis. Besides, it is necessary to explore how LCA could enhance the design of potential strategies to reduce emissions from passenger transport, which will be addressed in the following section.

3.2 Sustainable scenarios to decarbonise passenger transport in urban areas

Sustainable development will greatly depend on quotidian choices so transport preferences should be shifted to combine human health, global climate and sustainable development goals (Intergovernmental Panel on Climate Change [IPCC], 2022). It has been estimated that around 55% of the reductions in the transit towards net zero global emissions will be 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 emission reduction of 4% on the path to net zero (International Energy Agency, 2021).

Moreover, if 20-50% of car trips are shifted to buses, and the remainder is replaced with active means of transport and public vehicles, the world could save 320 Mt CO2-eq by the mid-2030s (International Energy Agency, 2021). Combining transport management with other mobility measures for emission reduction has also proven to be effective in the urban context. For instance, a case study in China compared four scenarios to reduce the carbon released by the transport sector. The measures 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 (Zhang et al., 2020).

Another study 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. It was 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 minutes longer than high-emission trips (Yang et al., 2018).

In spite of these findings, there were no feasible scenarios found in the literature review including comparative measures to reduce the carbon emissions of passenger transport, using a life-cycle perspective. Very little is currently known about the environmental benefits associated with mobility strategies based on LCA and 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 documented, but sustainable scenarios regarding the population transported by vehicle type and the lifetime mileage of each transportation system have been less researched. Most of the reviewed studies have taken into account direct exhaust fumes instead of considering life-cycle impacts in the proposal of new mobility scenarios. In addition, scientific efforts are also required in order to establish criteria for vehicle replacement in the implementation of low-carbon scenarios. To this end, it is necessary to analyse the efficiency of scrappage schemes in boosting vehicle electrification, as it has been tackled in this thesis.

3.3 Scrappage schemes and the optimisation of the lifespan of vehicles

Vehicle replacement has been found to be a logical response to environmental issues such as air pollution and Greenhouse Gas (GHG) emissions associated with old cars, since about 17% of the oldest vehicles analysed in a case study in the United States contributed to 50% of total fleet mass emissions (Bernard et al., 2020). Several countries have applied scrappage schemes with the aim of accelerating the adoption of cleaner vehicles, by taking old vehicles out of the fleet as well as boosting the vehicle industry. However, the efficiency of these measures depends greatly on the long-term use of the new cars, so that CO_2 emissions would only decrease if the new vehicles are kept in use for at least 4.7 years, as shown in a Japanese case study carried out by Kagawa et al. (2013).

Another research showed that there were no environmental benefits related to a scrappage scheme in Spain, given that its capacity to create new demand for more energy-efficient vehicles was found to be about 20%, while the percentage required to make this measure environmentally beneficial from a perspective of the Public Administration is estimated to be 30% (Jiménez et al., 2016). In this sense, optimising the lifetime of vehicles could be an alternative to fleet renewal since this approach has the potential to reduce vehicles' life-cycle emissions by up to 35%, while it is considered as a key in the transformation pathway towards reducing the emissions associated with private transportation (World Economic Forum, 2021).

Furthermore, the European Union has set the goal of preventing waste generation by promoting long-lasting products (European Commission, 2015). The problem with this approach is the possibility of discounting consumed energy and impacts from usage. Increasing a product's lifetime does not guarantee a reduction in environmental impacts, since older and less efficient products may generate higher impacts in extended usage than newer options (Hummen & Desing, 2021).

In line with this, Ardente & Mathieux (2014) measured the durability of energy-using products with the aim of establishing the potential benefits of lifetime extension as compared with those of substitution with better performing alternatives. This research detected significant life-cycle environmental benefits of extending the lifetime of certain products, but this generally depends on the impact category and the efficiency of the replacement product. The study concluded that this kind of assessment is suitable for product groups characterised by rapid technological change, which they illustrated by testing this method on washing machines.

Also, Alejandre et al. (2022) have applied LCA to study the operational lifespan of household appliances. To establish environmentally optimal operating periods, the research quantified the GWP of a microwave oven, a dishwasher and a washing machine and tested sustainable scenarios to reduce their carbon footprints through lifespan-based strategies. Nonetheless, it is pertinent to address the specific conditions of the automotive sector in order to establish an optimum vehicular lifespan.

Life extension is a priority strategy in order to optimise the environmental performance of energy-using products, but one that has an important drawback in that there is a lack of developed knowledge about long-lasting product design (Bakker et al., 2014). Despite this, several studies have addressed the connection between environmental impacts and the lifetime of automotive products. For instance, Kim et al. (2003) showed that optimal lifetimes are inversely correlated to annual vehicle mileage, hence lifetimes ranging from 7 to 14 years are optimal for a mid-sized car replacement based on LCA.

Dewulf & Duflou (2004) proved that the optimal environmental lifetime for an average passenger car is 11.5 years but this estimation is not specific to a particular vehicle type, and thus does not analyse replacement options since they use a general approach without a specific degradation rate nor a propulsion system-based alternative. Suggested optimal lifetimes of vehicles have been better reported, but much less is known about the emission savings ratio and the environmental performance of the substitution options. Exploring how LCA can be applied to optimise vehicle lifespan in order to establish an alternative approach to decarbonise urban passenger transport is an issue that will be tackled in the present doctoral thesis.

Table 1. Summary of the literature review.

GHG and life-cycle emissions from passenger transport	
Findings	**Source**
15% of the global GHG came from transport. The land modes of transport have the third highest average annual emissions growth with a 10% contribution to global GHG.	(IPCC, 2022)
Policies such as the Kyoto Protocol and the Paris Agreement have been designed to reduce GHG emissions, promoting energy decarbonisation and transport electrification.	(Kazancoglu et al., 2021)
A petrol car emits 192 g CO2-eq·pkm-1, while the carbon footprint of a motorcycle is 46.4% lower: 103 g CO2-eq·pkm-1. These data do not consider life-cycle impacts.	Tiseo (2021)
LCA has been used to evaluate the environmental efficiency of vehicles from a comprehensive perspective, but some factors affect the emission measurement e.g., functional units, vehicle type, geographical differences and driving conditions.	(Xia et al., 2022)
A consistent comparison of vehicle GHG emissions results found in reviewed literature requires an accurate harmonisation to avoid assumptions which may vary significantly across time and different geographies.	(Raugei, 2022)
Sustainable scenarios to decarbonise passenger transport in urban areas	
Findings	**Source**
Sustainable development will greatly depend on quotidian choices so transport preferences should be shifted to combine human health, global climate and sustainable development goals.	(IPCC, 2022)
55% of the reductions in the transit towards net zero global emissions will be related to consumer choices. Replacing private vehicle commuting with cycling or public transportation will provide an additional emission reduction of 4%.	(International Energy Agency, 2021)

If 20-50% of car trips are shifted to buses, and the remainder is replaced with active means of transport and public vehicles, the world could save 320 Mt CO2-eq by the mid-2030s.	(International Energy Agency, 2021)
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%.	(Yang et al., 2018)
A combination of public transport management and switching to natural gas fuel resulted in the highest reduction in carbon emissions (40.28%), in a Chinese case study.	(Zhang et al., 2020)

Scrappage schemes and the optimisation of the lifespan of vehicles

Findings	**Source**
17% of the oldest vehicles analysed in a case study in the United States contributed to 50% of total fleet mass emissions.	(Bernard et al., 2020)
The efficiency of scrappage schemes depends greatly on the long-term use of the new cars, so that CO2 emissions would only decrease if the new vehicles are kept in use for at least 4.7 years, as shown in a Japanese case study.	Kagawa et al. (2013)
There were no environmental benefits related to a scrappage scheme in Spain, given that its capacity to create new demand for more energy-efficient vehicles was found to be about 20%, while the percentage required to make this measure environmentally beneficial is estimated to be 30%.	(Jiménez et al., 2016)
Optimising the lifetime of vehicles could be an alternative to fleet renewal since this approach has the potential to reduce vehicles' life-cycle emissions by up to 35%.	(World Economic Forum, 2021)
Optimal lifetimes are inversely correlated to annual vehicle mileage. Lifetimes ranging from 7 to 14 years are optimal for a mid-sized car replacement based on LCA.	Kim et al. (2003)
The optimal environmental lifetime for an average passenger car is 11.5 years. However, this estimation does not analyse replacement options since a general approach without a specific degradation rate nor a propulsion system-based alternative is used.	Dewulf & Duflou (2004)

This literature review has allowed us to establish that sustainability of passenger transport is now widely researched and that several approaches are currently applied to shift towards a low-carbon mobility in the city. However, there have been no controlled studies using a life-cycle perspective to (1) analyse the differences between carbon emissions in urban and rural settings, (2) design suitable strategies to specific urban settings and (3) optimise the replacement of old vehicles as a measure to achieve environmental benefits. In this work we quantify the environmental impacts of public and private vehicles to comprehensively clarify the potential strategies that a city could implement to significantly reduce the life-cycle emissions from passenger transport.

This research demonstrates that factors such as distance travelled and the number of daily trips have an important influence on the passenger transport emissions, particularly in urban settings whose private vehicles emit, on average, 120% more carbon emissions than those of rural settings. It has been also demonstrated 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. In addition, this work exposes that ensuring a renewable energy mix is key in vehicle electrification inasmuch as the replacement of an old petrol car with an electric vehicle could be up to 69.94% faster if a cleaner energy mix is used to run the replacement car.

This thesis corresponds to an article compilation comprised of three main scientific contributions and a conference article. Firstly, the goals and the hypothesis of the research will be presented. The methodology section describes how LCA was used to quantify GWP of public and private vehicles in order to compare carbon emissions in urban and rural settings and propose effective measures to reduce the environmental impacts associated to passenger transport. The three main contributions and the conference article are exposed before a summary of results in Section 10. Finally, the main findings are discussed followed by the conclusions which draw up how this work represents a novel contribution in the use of LCA in the target of reducing carbon emissions in the city.

4. Objectives and hypotheses

4. Objectives and hypotheses

General objective: To estimate the life-cycle environmental impacts of private and public passenger vehicles, with the purpose of analysing potential strategies to reduce their GWP and shift to a sustainable passenger transport in urban contexts.

General hypothesis: Enhancing the use of public transport and promoting vehicle electrification are key conditions to meet sustainable transport in urban scenarios.

- **Specific objective 1:** To comprehensively clarify the differences between urban and rural settings when estimating and comparing life-cycle carbon emissions from private transportation systems.

  Specific hypothesis 1: The private vehicles used in an urban setting emit greater amounts of carbon dioxide than those driven in rural areas, considering the low average occupancies reported in the Colombia's capital city for private vehicles.

- **Specific Objective 2:** To simulate eight scenarios designed to reduce the total annual carbon emissions from passenger transport in a city, taking into account the Global Warming Potential of public and private vehicles, obtained by means of LCA.

  Specific hypothesis 2: 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.

- **Specific objective 3:** To establish the environmentally optimal time within which to replace a petrol car, using a life-cycle perspective to analyse the impacts of the substitution options.

  Specific hypothesis 3: Replacing an Internal Combustion Engine Vehicle (ICEV) with a Battery Electric Vehicle (BEV) would only be worthwhile if the substitution option is run with a renewable energy mix, since clean electricity has proven to be effective in increasing the environmental benefits of using electric cars.

- **Methodological objective 1:** To compare the outcomes of Life Cycle Assessments performed on a passenger vehicle using two different technological approaches: the product system modeller of OpenLCA and the module for sustainable design of SolidWorks.

  Methodological hypothesis 1: The results of Global Warming Potential and Total Energy Content obtained from OpenLCA are more accurate than those from SolidWorks, in spite of using the same inventories in both modelling processes.

Figure 2 illustrates the structure used in this Doctoral Thesis to establish the specific goals and the projected achievements:

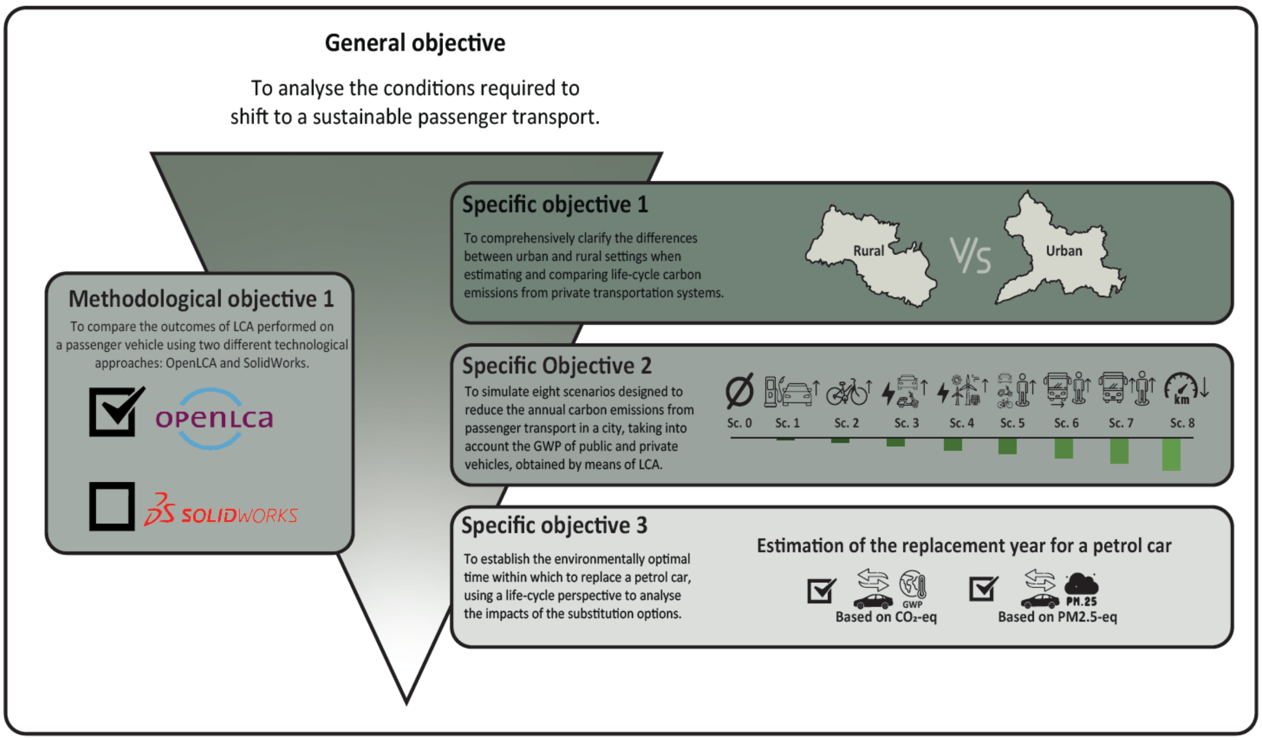

Figure 2. Summary of the methodology for the thesis.

5. Methodology

5. Methodology

In this thesis, we first compared the life-cycle carbon emissions yielded by two different technological approaches: OpenLCA and SolidWorks. For such purpose, a 17.23 kg conventional bike was analysed, using the same inventories in both software tools. The assessments allowed us to establish that OpenLCA offers a more proper approach to model the product system of a vehicle, when compared to the module of sustainable design of SolidWorks. These learnings allowed us to address the methodological objective described in Section 4 and were finally included in the conference article which can be seen as the fourth contribution of this work.

In this sense, the analyses carried out in this research followed the procedure established by ISO 14044 for LCA and performed the stages of goal and scope definition, inventory, impact assessment and results interpretation on private and public vehicles, by means of OpenLCA. The life-cycle inventories were mostly obtained from the Ecoinvent 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. 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).

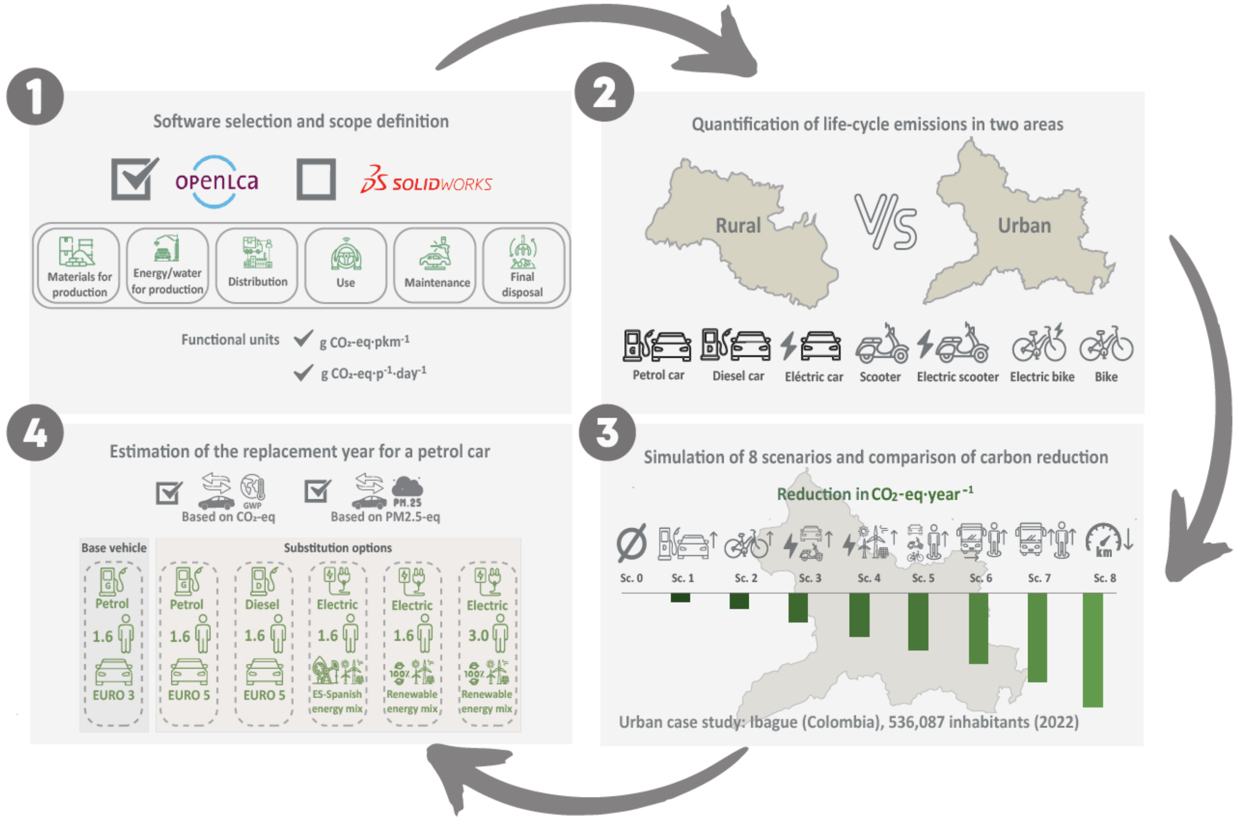

Figure 3. Summary of the methodology for the thesis.

5.1 Comparison of the life-cycle carbon emissions of vehicles in urban and rural settings

For the first part of the research, two case studies have been chosen: Ibagué and Venadillo, both located in Tolima, which is a province in the central region of Colombia. These towns represent two different cases of Tolima. On the one hand, a capital city with a considerable vehicle census and, on the other, a rural town with a less clearly defined mobility trend on the other. The vehicular census of electric and conventional bikes, scooters and cars were estimated for each area, including internal combustion engine automobiles based on diesel and petrol.

The LCA yielded the GWP of the selected means of transport, which was expressed in g CO_2-eq·pkm^{-1} by using the lifetime performances and the specific average occupancies of the vehicles used in each studied area. Additionally, the per-person daily grams of emitted CO_2-eq were calculated by computing these results with the average travelled distance and the average number of daily trips, in order to compare local tendencies in the passenger transport emissions of Ibagué and Venadillo. To address the differences between the environmental impacts of automobiles, motorcycles and bicycles, weighted averages of daily emissions have been calculated taking into account the fleet size of each vehicle category.

5.2 Proposal of carbon emission reduction scenarios for a medium-sized city

In this contribution we assessed eight settings designed to decarbonise traffic and improve environmental conditions related to commuting and passenger transport in Ibagué, as part of a case study aimed at analysing potential mobility strategies in a medium-sized city. To this purpose, the fleet sizes, the average distance travelled and the GWP of the city's private vehicles were obtained from our first contribution, explained in section 4.1. Measures such as increasing the usage of sustainable vehicles, decreasing mobility by shifting commuting patterns, and augmenting the city's public vehicle fleet were modelled with the aim of comparing their environmental performance.

A base-scenario with the current situation of carbon emissions in Ibagué was established as the first set of results of this study, calculating the GWP of local regular buses by means of OpenLCA, in order to consider public transport in our estimations. The modal shares were modified in accordance with the fleet increments required to establish the hypothetical measures that compose the designed scenarios. Variables such as average trips per day, population by means of transport, energy mix in the electricity market and average occupancy of public and private vehicles were also modified in order to analyse the total carbon emissions from passenger transport in each proposal.

5.3 Optimal replacement scenarios for an average petrol passenger car

In this part of the research, we performed an LCA which yielded the per passenger-kilometre carbon emissions of a petrol car and the GWP of five substitution options including a EURO 5 petrol car, a EURO 5 diesel car, and an electric car with different energy mixes. To establish the environmentally optimal time within which to replace the base vehicle, the contributions to GWP were placed into two categories: (1) Embodied Carbon (EC), which includes the acquisition of raw materials, manufacture and end-of-life, and (2) Operational Carbon (OC), which corresponds to the use phase, including the maintenance of the automobile during its lifetime.

For each substitution option, a comparison is made between the potential emission savings associated with continuing to use the old car and those associated with the replacement option, in order to find the environmentally optimal ratio for the replacement of the old car. In this approach, the emissions from the manufacturing and end-of-life processes of the new car would be saved if the old car were used, instead of replacing it. In contrast, if the new car were used, the excess emissions from the old car would be saved. This analysis allowed us to simulate each replacement scenario and observe the evolution of the emission savings ratio over time with the aim of establish a proper replacement year in accordance with the environmental performance of each substitution option.

6. Measuring life-cycle carbon emissions of private transportation in urban and rural settings

6. 1st article: Measuring life-cycle carbon emissions of private transportation in urban and rural settings

Journal: Sustainable Cities and Society (Impact factor: 11.7 - Q1)

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6.1. Conflicts of interest

The authors declare no competing financial interest.

6.2. Acknowledgements

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6.3 Highlights

- This study quantifies carbon private transport emissions in rural and urban settings.
- A low developed rural area shows a less pollutant transportation pattern than the selected urban area.
- This study provides specific emissions for seven private transportation type during the life cycle.
- This research provides better understanding for policymakers to boost sustainable private transportation.

6.4 Abstract

The current fossil fuel-based passenger transport model does not correspond to the specific characteristics of the different urban and rural realities, so the shift to sustainable transport needs to be performed by understanding the particularities of each case. Thus, the goal of this research has been to comprehensively clarify the differences between urban and rural settings when estimating and comparing life-cycle carbon emissions from private transportation systems. From the Colombian region of Tolima, we have selected for analysis the municipalities of Ibagué and Venadillo as urban and rural areas, respectively. Private transportation systems have been modelled through a Life-Cycle Assessment (LCA) that allowed us to obtain the Global Warming Potential (GWP) of gasoline, diesel and electric cars, electric and fuel-based motorcycles and electric and conventional bikes. The results show that, on average, emissions from the analysed urban area (140 g CO_2-eq·pkm^{-1}) are 23% higher than those of the rural case study (110 g CO_2-

eq·pkm^{-1}). This article concludes that, if the average travelled distance and number of per-day trips are taken into account, great differences are striking: for the capital city of Tolima, the average daily emissions per passenger (2,000 g CO_2-eq·p^{-1}·day^{-1}) is 120% higher than that of the rural area.

Keywords: transportation systems, life-cycle assessment, greenhouse gas emissions, passenger travel, global warming, carbon footprint.

6.5 Graphical Abstract

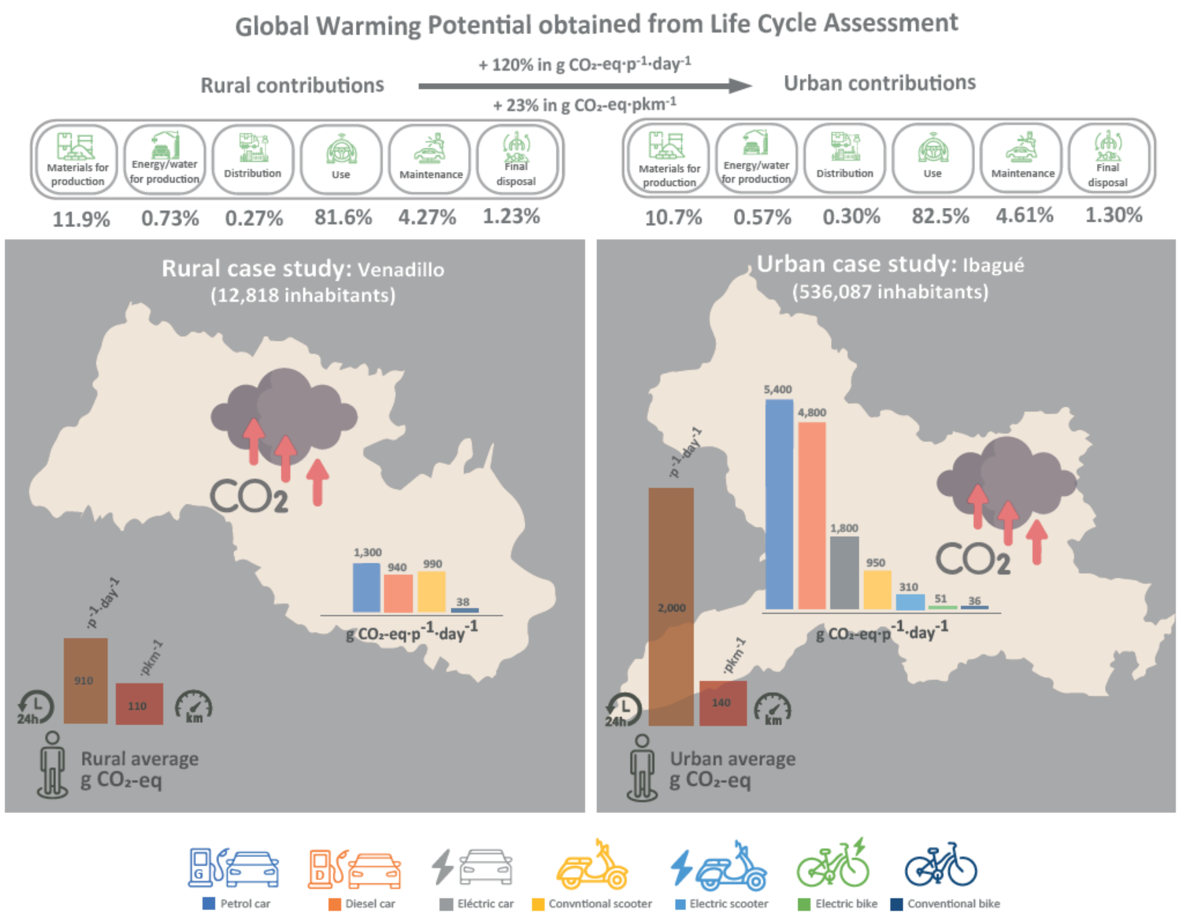

Figure 4. Graphical abstract of the second paper

6.6 Introduction

Over the last decade, global Greenhouse Gas (GHG) emissions have grown by an annual average of 1.3%, reaching the amount of 59 gigatons of carbon dioxide equivalent (Gt CO2-eq) in 2019, of which 15% (8.7 Gt CO2-eq) came from transport. Moreover, 70.1% of the 8.7 Gt CO2-eq emissions from transport corresponds to land modes, including passenger and freight transportation, with a 10% contribution to global GHG. This is the subsector with the third highest average annual emissions growth, surpassed only by metals and land use, and land-use change and forestry (Intergovernmental Panel on Climate Change [IPCC], 2022). Hence, it has the responsibility and opportunities to contribute to the achievement of the sustainable development goals by consuming renewable energy sources instead of fuel-based ones, and regulating the use of more environmentally-convenient transport services for each area, for instance.

Tiseo (2020) compared the carbon footprints of selected vehicles such as automobiles, motorcycles and bicycles, by analysing worldwide data on travelled kilometres per passenger transported. He found that, while a petrol car emits 192 grams of carbon dioxide equivalent per passenger-kilometre (g CO_2-eq·pkm^{-1}), the carbon footprint of a motorcycle is 46.4% lower: 103 g CO_2-eq·pkm^{-1}. However, this study omitted the emissions from stages such as the vehicle's production or end-of-life, which underlines the relevance of applying a life-cycle perspective when comparing CO_2 emissions from fuel-based means of transport, including four- and two-wheel vehicles.

In this context, the reduction of emissions by means of the electrification of two-wheel vehicles has been analysed in several studies. Tuayharn et al. (2015) compared the GHG emissions of a motorcycle equipped with an internal combustion engine, with those of an electric motorcycle in Thailand. The study exposed that the former releases 43.6 grams of carbon dioxide per kilometre travelled, while this emission reaches 20.7 grams in the case of electric motorcycles, if coal-generated electricity is used. It is important to point out that if the electricity generation system is switched to natural gas, CO_2 emissions would be reduced to 10.7 grams per kilometre.

With respect to four-wheel vehicles, it is worth mentioning a study carried out by Morfeldt et al. (2021) that exposes a specific tailpipe CO_2 emission of 173 g $CO_2 \cdot km^{-1}$ for Internal Combustion Engine Vehicles (ICEVs). Also, in a comparative study of BEVs and ICEVs made in China, Zheng and Peng (2021) found that the former can reduce CO_2 in the range of 17-34%, when compared with ICEVs. Nonetheless, this depends on a country's power generation system: in countries with dominant coal power generation, CO_2 emissions of BEVs can be even higher than those of ICEVs. This situation exposes the need for studies based on Life-Cycle Assessment (LCA), given that it may not be enough to electrify transportation in a region but also to decarbonise its electricity generation system.

Some other studies have been performed in laboratory conditions to compare two- and four-wheel vehicles. For instance, Szymlet et al. (2019) corroborated the importance of internal combustion engine characteristics. They found that a motorcycle can emit more CO_2 than a light passenger car during drive testing, depending on to the efficiency of spark-ignition engines: the lower the efficiency, the higher the fuel consumption and emissions. While the laboratory conditions do not represent the vehicles' real performance, this case lays bare the importance of taking into account all the particular characteristics of a vehicle.

Currently, the conventional bicycle is considered an essential means of urban transport for the purpose of implementing sustainable urban mobility plans and promoting the use of alternative high-efficiency and low-emission transport means (Wałdykowski et al., 2022). Thus, it has been established that an electric bike emits 22 g CO_2-eq·km^{-1} while a conventional bike releases 16 g CO_2-eq·km^{-1}, with an average occupation of 1 passenger and a lifespan of 15,000 km (Philips et al., 2022). Furthermore, it has been found that an electric scooter, model Vespa Elettrica, produced in Italy and powered by Germany's electricity mix, emits 64.5 g CO_2-eq·km^{-1}; while a conventional four-stroke scooter, EURO 4, produced in Asia and driven in Berlin emits 73.0 g CO_2-eq·km^{-1} (Veiga, 2020), both with an average occupancy of 1.1 passengers and a lifespan of 50,000 km.

In addition, the Global Warming Potential (GWP) of an average Internal Combustion Engine Vehicle has been found to be 226 g CO_2-eq per kilometre travelled, while that of an average BEV is estimated to be 77 g CO_2-eq per kilometre travelled; when comparing small-sized cars in terms of life-cycle GHG emissions (Bieker, 2021). In summary, *Table 2* shows the life-cycle CO_2 emissions of the two- and four-wheel vehicles cited previously, from smallest to largest:

Table 2. Comparative of global warming potential from life cycle of transportation systems.

Global Warming Potential (GWP) measured in g CO_2-eq·pkm^{-1}			
Vehicle	**Lifetime performance (pkm)**	**Emissions per functional unit (g CO_2-eq·pkm^{-1})**	**Source**
Bike	15,000	16	Philips et al. (2022)
E-bike	15,000	22	Philips et al. (2022)
E-scooter	55,000	64.5	Veiga (2020)
Scooter	55,000	73.0	Veiga (2020)
Electric car	225,000	77	Bieker (2021)
ICEV	200,000	226	

LCA has been widely used to evaluate the environmental efficiency of vehicles from a more comprehensive perspective (Wang & Tang, 2022). However, factors such as system boundaries, functional units and vehicle type could affect the calculation of carbon emissions of vehicles, varying greatly due to geographical differences in the power structure, ambient temperature, and driving conditions (Xia et al., 2022). In this sense, to generate useful information for urban mobility planning and policy design, it is necessary to include as many vehicle categories as possible when making a life-cycle impacts comparison, taking into account propulsion systems based on diesel, gasoline and electricity for two- and four-wheel vehicles.

Also, the data of life-cycle CO_2 emissions obtained from a review of the literature present a significant drawback in that they address specific means of transport with no comparative analysis related to a particular region: according to Raugei (2022), a consistent comparison of vehicle GHG emissions results found in reviewed literature requires an accurate harmonisation to avoid assumptions which may vary significantly across time and different geographies. In this respect, it has been detected a gap of knowledge regarding the impacts related to the usage of private vehicles linked to a certain region and the respective characteristics of its private vehicle fleet.

To restrain the increase of climate disasters, countries around the world have been replicating the global warming mitigation objectives at all levels, adapting them to regions and cities by means of locally relevant policy measures that intend to mitigate global warming: for instance, the European Union has set an objective of reducing a 55% its GHG emissions by 2030 and achieving carbon neutrality in 2050 (Dorr et al., 2022). In accordance with Kazancoglu et al. (2021), policies such as the Kyoto Protocol and the Paris Agreement have been designed to reduce GHG emissions in countries, promoting energy decarbonisation and transport electrification. To such purpose, vehicle emissions should be estimated and compared, as a first step in the analysis of the current road transport situation in each geographical area.

Against this backdrop, the goal of the present study is to comprehensively clarify the differences between urban and rural settings when estimating and comparing life-cycle carbon emissions from private transportation systems. As a novel contribution, the total carbon emissions of two geographical areas have been contrasted by analysing private fleet size (1), vehicle specifications (2), average occupancy (3), daily trips (4) and daily distance travelled by vehicles (5). Thus, the present research addresses not only emissions from private vehicles, but also environmental performances related to specific settings and social habits.

The results are shown in terms of GWP, measured in CO_2-eq·pkm^{-1} and carbon dioxide equivalent per person-day (CO_2-eq·p^{-1}·day^{-1}) for each studied area. The research was carried out in Tolima, a central region of Colombia, choosing Ibagué as an urban case study, and Venadillo as rural. The GWP of the private transportation systems was carried out analysing seven private transport types of vehicle (gasoline, diesel and electric cars, electric and fuel-based motorcycles and electric and conventional bikes). It is important to state that Ibagué is the capital city of Tolima, while Venadillo is a town of which 99.6% is located in the rural area (Concejo Municipal de Venadillo, 2020).

The comparative study was based on the extrapolation of CO_2 emissions from each vehicle type, taking into account the size of the vehicle fleets and the number of daily trips made by citizens in each of the areas. This article will first describe the chosen methodology based on LCA, followed by the results of the study. The discussion chapter shows the comparison of results of this research and those of previous studies in different areas. Lastly, the conclusions section draws up the specific findings of this research when comparing the urban and rural areas analysed.

6.7 Methodology

To compare the environmental impacts of passenger transport in the selected urban and rural settings, the carbon emissions from private vehicles have been estimated through an LCA performed in commonly-used cars, motorcycles and bikes. Therefore, this chapter will firstly expose how the fleet sizes were calculated in order to address the available vehicles of Ibagué and Venadillo for the local-scaled analysis. Secondly, the estimation of the average travelled distance will be explained before describing how the average of daily trips was determined for each area. Finally, the goal, scope and assumptions for the LCA are detailed in Sections 2.4, 2.5 and 2.6.

6.7.1 Target population and sample

For this research, two case studies have been chosen: Ibagué and Venadillo, both located in Tolima, which is a province in the central region of Colombia. It has 47 municipalities in total, of which 60% are made up of 50% rural areas. In 2020, a census of 1,339,998 inhabitants was registered, 40% of which population lives in Ibagué, its capital city (Gobernación del Tolima, 2020). Located west of the centre of the province, Ibagué has, in total, 536,087 inhabitants and a population density of 372.5 inhabitants per km^2 spread over 445 neighbourhoods (Alcaldía Municipal de Ibagué, 2020). One of its bordering municipalities is Venadillo, a town also included in this study that is located in the north of Tolima, with a surface area of 335.3 km^2, of which 99.6% is made up of rural zones. In total, Venadillo is home to 12,817 inhabitants, spread across 30 villages (Concejo Municipal de Venadillo, 2020). Within this study, Ibagué and Venadillo represent two different cases of Tolima: a capital city with a considerable vehicle census on the one hand, and a rural town with a less clearly defined mobility trend on the other. Taking the calculation of GWP as a goal for this research, it is important to address the vehicular census of electric and conventional bikes, scooters and cars for each area, including internal combustion engine automobiles based on diesel and petrol.

Firstly, Ibagué has a fleet of 217,671 vehicles (Centro de Información Municipal para la Planeación Participativa, 2021). Due to the lack of data about internal combustion engine vehicles based on diesel and petrol, it was necessary to assume that these automobiles have the same modal shares as those registered for Colombia: according to Universidad de Antioquia (2020), there are 3,556,134 petrol cars, 8,996,032 petrol motorcycles and 27,555 diesel cars out of the 15,627,240 vehicles driven in the country (Ministerio de Transporte, 2021), meaning a modal share of 23%, 58% and 0.2% for these transport systems, respectively. If these percentages are applied to Ibagué's fleet, it is fitting to estimate a vehicular census of about 50,000 petrol cars, 130,000 petrol motorcycles and 390 diesel cars.

In regard to the number of electric vehicles in this city, it was appropriate to calculate the motorisation index for the purpose of estimating the number of electric cars, e-bikes and electric motorcycles driven in Ibagué. *Table 3* shows these estimations based on data obtained from the Ministerio de Transporte (2021) and Registro Único Nacional de Tránsito (2021). It is important to clarify that vehicle quantities per thousand inhabitants are calculated from the national census and current population of Ibagué: 48,258,494 inhabitants (Departamento Administrativo Nacional de Estadística [DANE], 2021) and 536,087 inhabitants (Alcaldía Municipal de Ibagué, 2020), respectively. In addition, the e-bike quantity presented is an approximation calculated by Jaramillo (2017).

Table 3. Estimation of vehicular census in Ibagué and Venadillo

Vehicle	**National quantity**	**Quantity per 1000 inhabitants**	**Estimation for Ibagué**	**Estimation for Venadillo**
Electric car	1,726	0.036	19	0.0
Electric motorcycle	1,377	0.029	16	0.0
E-bike	440,000	9.1	4,900	0.0
Used sources for estimation	(Registro Único Nacional de Tránsito, 2021)			Mobility survey of the present research

With respect to conventional bicycles, 3% of Ibagué citizens use this transportation mode, according to research by the Universidad de Ibagué (2022). Taking into account the current population of the city, we were able to estimate a total of about 16,000 bikes driven there. Regarding the number of electric vehicles driven in Venadillo, *Table 3* shows an estimation based on a survey we performed for the calculation of the modal share and the average travelled distance, since there is no mobility department or any other agency in charge of controlling vehicle fleet in this area. To such purpose, a 3.4% sample was selected from the 940 residential-used middle-class houses spread across the rural zone of Venadillo (DANE, 2023). The sample size was determined to be 32 individuals, which falls within the commonly-used range of 3-6% of a city's households for Colombian studies aimed at understanding the inhabitants' journey pattern, as reported by Flores & Gonzalez (2007).

The number of applied surveys corresponds to a 0.24% of Venadillo's population, which is aligned to the percentage applied in the Bogotá Mobility Survey (Secretaría |de Movilidad de Bogotá, 2019). The study carried out 17,557 validated surveys among a population of 7,181,469 citizens of the capital city of Colombia (DANE, 2021). This estimation is also aligned to a survey carried out in Spain which selected 27,832 individuals (Instituto Nacional de Estadística, 2008a) from a population of 16,694,712 (Instituto Nacional de Estadística, 2008b), taking a sample of 0.17% for the analysis of average travelled distance per family-use vehicle.

6.7.2 Average distance calculation

With the aim of making a comparison of the CO_2 emissions between the vehicles in Ibagué and those in Venadillo, it was necessary to take the results of a GWP analysis of each transportation system, given in g CO_2-eq·pkm^{-1}, and multiply them by the average distance (km per trip) for each town and the average number of trips made by each vehicle (trips per day). This was for the purpose of converting emissions per passenger-kilometre to emissions per passenger-day in each city. To such purpose, we estimated the average distance travelled for Ibagué by taking into account the average time per trip and average speed of the vehicles, as established by the Consejo Nacional de Política Económica y Social (2020). *Table 4* shows the average distance calculation with data specific to Ibagué.

Table 4. Estimation of average distance travelled of transportation systems of Ibagué

Vehicle	Average time per trip (h)	Average speed (km per h)	Average distance travelled for Ibagué (km)	Average distance travelled for Venadillo (km)
Petrol car	0.40	24	9.6	2.1
Diesel car			9.6	2.0
Electric car			9.6	0.0
Conventional scooter	0.30	26	8.8	3.8
Electric scooter			8.8	0.0
Electric bike	0.40	15	6.2	0.0
Conventional bike			6.2	1.1
Used sources for estimation	Consejo Nacional de Política Económica y Social (2020)			Mobility survey of the present research

It is worth noting that the average bicycle speed showed in *Table 4* was obtained from the research carried out by Ortiz Betancourt (2015) on bicycle commuting in Ibagué. Meanwhile, there are no available datasets for the calculation of average distance travelled in Venadillo, hence it was necessary to apply a mobility survey to a selected sample, as previously mentioned. The most important questions in the survey referred to vehicle type (petrol car, diesel car, electric car, petrol motorcycle, electric motorcycle, bicycle or e-bike), year of production, passenger occupancy in normal conditions, distance travelled per trip, and number of trips per day. The results are shown in *Section 3* along with the outcomes of the modal shares analysis for Venadillo.

6.7.3 Average number of trips per day

As previously explained, an estimation of the number of trips per day made by each vehicle is required for the purpose of comparing local CO_2 emissions. Notwithstanding, the same information on urban mobility in Ibagué is not available for Venadillo, hence estimations were made in two different ways. In the first case, the Consejo Nacional de Política Económica y Social (2020) indicates that 905,000 trips are made in a typical day in Ibagué: 100,507 trips correspond to private cars, 136,553 are made by motorcycle and 8,195 correspond to bicycles. Taking into account the city's vehicular census, according to the fleet estimation made in *Section 2.1*, it is feasible to calculate the average number of trips per day for each vehicle by dividing the daily total number of trips by the total estimated fleet.

In the second case, the survey applied in Venadillo gave the modal shares of the vehicles analysed and an individual average number of trips per day for each transportation system used in that area. By applying the obtained modal shares to the current population of this area, we were able to obtain a detailed vehicular census. Meanwhile, the estimated average number of trips allowed us to convert emissions per passenger-kilometre to emissions per passenger-day for the same area. *Table 5* gathers the fleet sizes and number of daily trips estimated for both settings:

Table 5. Estimation of trips per day by transportation system in Ibagué.

Vehicle type	Transport system	Ibagué		Venadillo	
		Fleet (Units)	**Trips per day by vehicle (Num.)**	**Fleet (Units)**	**Trips per day by vehicle (Num.)**
Automobiles	Petrol car	50,000	2.0	2,400	2.3
	Diesel car	390	2.0	400	2.0
	Electric car	19	2.0	0.0	0.0
Motorcycles	Conventional scooter	130,000	1.1	6,000	3.9
	Electric scooter	16	1.1	0.0	0.0
Bicycles	Electric bike	4,900	0.4	0.0	0.0

Conventional bike	16,000	0.4	1,600	2.3

6.7.4 Goal and scope

Assessing the GWP of each transportation system addressed in this manuscript, measured in g CO_2-eq·pkm^{-1}, requires a well-stablished methodology that allows for an appropriate inventory of inputs and outputs from every process involved in the life cycle of the vehicles. In this sense, ISO 14044 standardises the requirements for LCA, offering the guidelines to carry out the stages of goal and scope, inventory, impact assessment and interpretation (Klüppel, 2005). By following this structure, it was determined that the goal for this research is the comparison of the CO_2 emissions, at all stages from cradle to grave, of seven types of individual transportation systems used in Ibagué and Venadillo: petrol car, diesel car, electric car, petrol motorcycle, electric motorcycle, conventional bike and e-bike. Concerning the scope of the study, the functional unit used for each vehicle was 1 passenger-kilometre (pkm). *Figure 5* illustrates the scope of the LCA performed for the seven vehicles, with the cradle-to-grave stages and the selected functional unit.

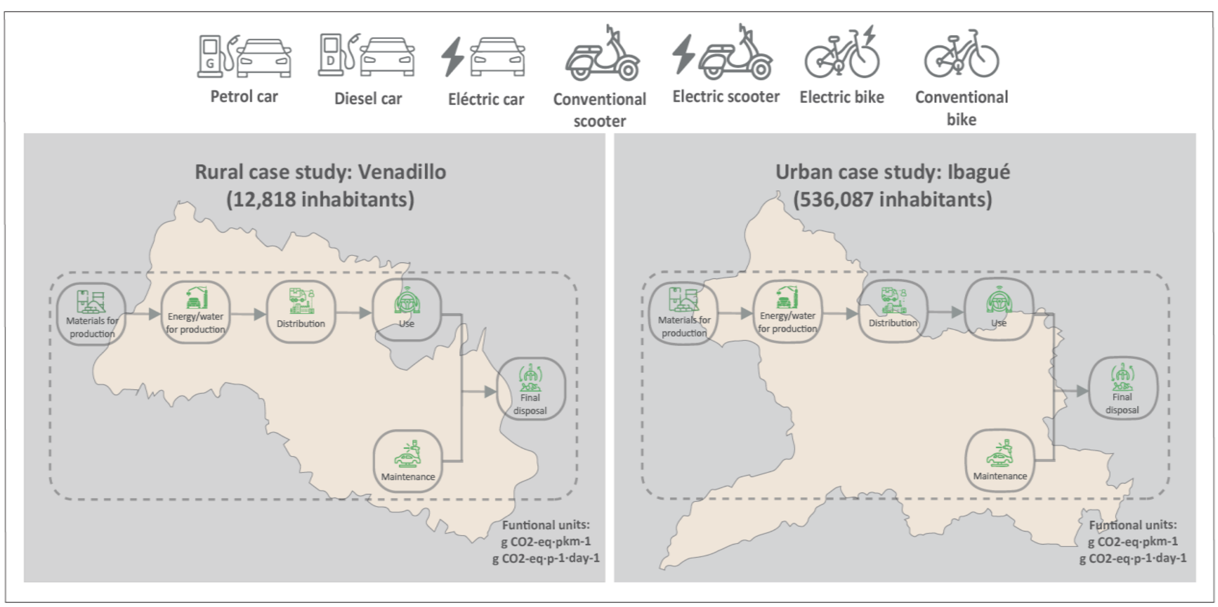

Figure 5. System boundaries for each vehicle analysed.

6.7.5 Life-Cycle Assessment (LCA) and comparison of transportation systems

According to van Lier and Macharis (2014), LCA is a method to analyse potential life-cycle environmental impacts, taking into account every stage from the extraction of resources, through production, use and recycling, to the disposal of remaining waste. For this research, LCA was executed using the Ecoinvent 3.8 dataset, while the cradle-to-grave environmental impacts of each transportation system were evaluated according to the life-cycle stages: acquisition, production, transportation, usage, maintenance and final disposal. Flows such as the energy, supplies and transportation for the extraction of raw materials, maintenance and supply chain-related processes were included in the analysis, as the providers involved in the product systems were also taken from Ecoinvent.

Furthermore, ReCiPe 2016 v.1.01 was used to calculate the GWP of every selected vehicle. This method comprises a Hierarchist (H) perspective that corresponds to a consensus model taken scientifically as a predetermined framework for the development of the current technology. Also, this is the most frequently used model for LCA at present, according to Shi et al. (2022). Meanwhile, characterisation factors at Midpoint level enable a low-uncertainty modelling process since they have a strong correlation to environmental impacts, through a set of indicators that can be used to express a wide variety of life-cycle-related substances, in terms of a limited number of environmental impact scores (National Institute for Public Health and the Environment, 2017). In addition to the Hierarchist perspective, characterisation factors at Midpoint level were also applied in this study.

6.7.6 Assumptions and sources for the Life-Cycle Inventory of selected transportation systems

Certainly, there were some assumptions required to prepare the life-cycle inventory of each vehicle selected. For instance, the reference model for the analysis of electric bikes was a 24-kg-weighted vehicle with a speed limit of 25 km/h, produced in Wuqing District, Tianjin City in China. Its lifespan is 15,000 km, with an average occupancy of 1 passenger. Distances between Wuqing District, Tianjin City and the usage point (Ibagué / Venadillo) were taken from Google Maps and SeaRates: 583 km from the production point to Quindao, China, where e-bikes are shipped for transoceanic transportation (Legiscomex, 2022); 17,231.5 km from there to Cartagena, Colombia, where vehicles are landed (SeaRates, 2022), and 1,047 km from there to Bogotá. The distribution finishes with a 203-km route from Bogotá to Ibagué and a 192-km route from Bogotá to Venadillo. It is assumed that the vehicle is distributed by a 7.5-16 ton freight lorry, EURO 3.

For the analysis of conventional bikes, a 17-kg-weighted regular city bike was selected, with a lifespan of 15,000 km and an average occupancy of one passenger. Distances for distribution were taken from Google Maps, assuming a logistics process starting in Bogotá. In the modelling process, it was assumed that the vehicle is distributed by a 3.5-7.5-ton freight lorry, EURO 3.

It is worth noting that the propulsion method of bicycles does not depend on fuel but passenger energy because of pedaling, hence the impacts of its usage do not include the GWP of flows such as petrol or diesel. In this respect, it has been detected that increasing the level of physical activity may bring diminishing returns in energy expenditure because of compensatory responses in non-activity energy expenditures (Careau et al., 2021), which means that calories spent while pedaling a bicycle do not necessarily lead to increased energy intake in human metabolism. Nevertheless, Severis et al. (2022) considered the caloric expenditure related to cycling in a comparative LCA performed on different modes of transport. In this approach, walking and cycling presented the lowest environmental impacts when compared to the usage of buses and cars, despite their GWP was found to be more sensitive to the inclusion of energy expenditure.

To consider the caloric intake in the present study, consumptions of 31 $kcal \cdot pkm^{-1}$ (Lacap & Barney, 2015) and 10.8 $kcal \cdot pkm^{-1}$ (Sivert et al., 2011) were taken into account for the powering of conventional and electric bikes, respectively. In addition, a per-kilocalorie food price of 1.0E-03 € was calculated, considering the latest Colombian per-kilogram food prices (DANE, 2023) and the composition of the Colombian food reported by Instituto Colombiano de Bienestar Familiar (2023). These data allowed us to estimate the total cost of necessary food for bike riding over a lifespan of 15,000 km (Supporting Information Table S1). The Exiobase 3.4 dataset was used for these estimations, with the CML 2001 Baseline methodology.

With reference to the electric motorcycle, a 144-kg weighted e-scooter with a speed limit of 70 km/h and an electricity demand of 3 kWh per 100 km was selected for the study. It is assumed that its production takes place in Wuxi, Jiangsu (China) and its lifespan is 50,000 km for an average occupancy of 1.1 passengers for Ibagué. In the case of Venadillo, average occupancy was calculated from the outcomes of the applied mobility survey. Distances for distribution were taken from Google Maps and SeaRates: 668 km from the production point to Quindao, China, where e-scooters are shipped for transoceanic transportation (Legiscomex, 2022); 17,231.5 km from there to Cartagena, Colombia, where the vehicles are landed (SeaRates, 2022), and 1,047 km from there to Bogotá. Finally, distribution is completed with a 203-km route from Bogotá to Ibagué and a 192-km route from Bogotá to Venadillo. It is assumed that the vehicle is distributed by > 32 t freight lorry, EURO 3.

For the conventional scooter analysis, a 90-kg-weighted motorcycle was selected, with a 4-stroke engine, classified in the 50-150 cc range. The duration of this vehicle is 55,000 pkm, because its lifespan is 50,000 km and its average occupancy is 1.1 passengers for Ibagué. In the case of Venadillo, average occupancy was calculated from the outcomes of the applied mobility survey. Production takes place in Pereira, Colombia, so distances for distribution are 114 km to Ibagué and 174 km to Venadillo according to Google Maps. There is no transoceanic transportation in this case, but land freight is made by a > 32 t lorry, EURO 3.

In relation to four-wheel vehicles, the present research addresses BEVs (Battery Electric Vehicles) and ICEVs (Internal Combustion Engine Vehicles), taking into account petrol and diesel cars; all of which are produced in South Korea. Assumptions for four-wheel vehicles are related to reference model, weight, lifespan, average occupancy and distances for distribution. In addition, a lifespan of 155,000 km and an average occupancy of 1.5 passengers for Ibagué were assumed, in accordance with the Alcaldía Mayor de Bogotá (2021). In the case of Venadillo, average occupancy was calculated from the outcomes of the applied mobility survey. Distances for distribution are 16,295 km from South Korea to Valle del Cauca, Colombia, where vehicles are landed after transoceanic trip, 888 km by land for usage in Ibagué and 823 km by land for usage in Venadillo, in a > 32 Ton EURO 3 lorry. *Table 6* provides the characteristics of the analysed four-wheel vehicles:

Table 6. Particularities of 4-wheel vehicles selected for this research.

Vehicle	Reference model	Engine power output	Weight	Used sources for inputs and outputs
Petrol car	Medium size	122 hp	1,212 kg	a) Emissions in usage: Asociación Colombiana de Vehículos Automotores (2017) (Supporting Information Table S2). b) The rest of inputs/outputs: Ecoinvent database.
Electric car	Medium size	109 hp	1,490 kg	a) Ecoinvent database.
Diesel car	Medium size	187 hp	1,600 kg	a) Ecoinvent database.

6.8 Results and discussion

6.8.1 Comparative of CO_2 emissions per passenger-kilometre of vehicles

The LCA performed in the present research yielded the GWP of the selected means of transport, which was expressed in g CO_2-eq·pkm^{-1} by using the lifetime performances and the specific average occupancies of the vehicles used in each studied area. Thus, the environmental impacts of private passenger transport in Ibagué and Venadillo were compared as shown in *Figure 6*.

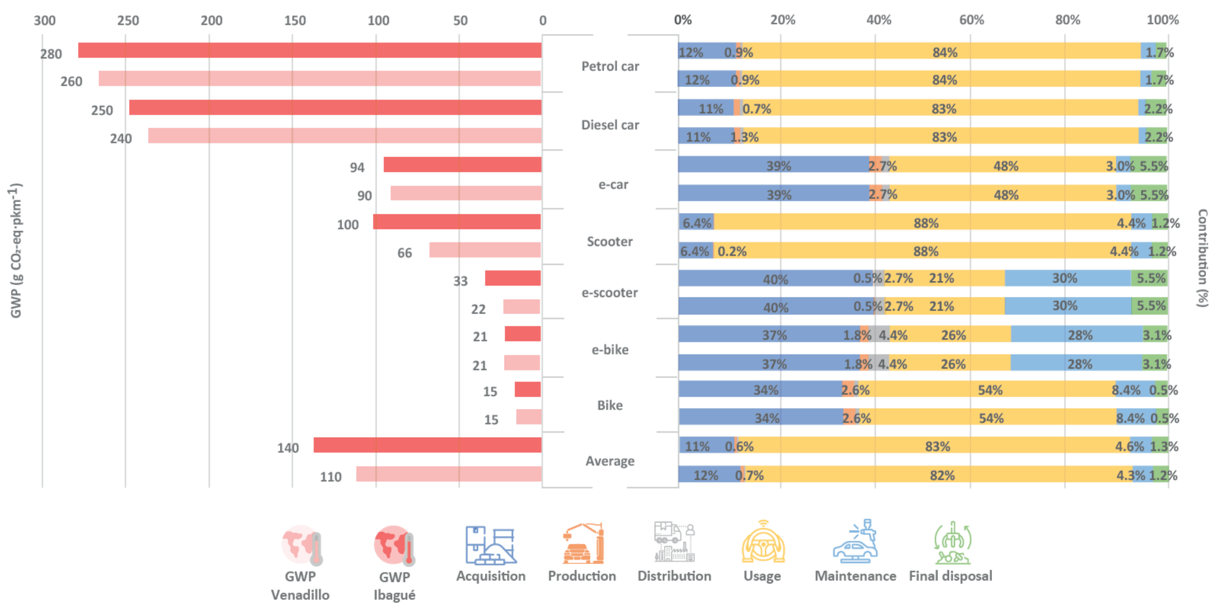

Figure 6. Comparative of CO2 emissions from transportation systems in Tolima.

Despite there being no technical differences between the vehicles analysed in each setting, it is possible to highlight that a one-kilometre trip made by one passenger in a petrol car used in Ibagué brings about 280 g of life-cycle carbon emissions. Meanwhile, if the use phase of the vehicle takes place in Venadillo, with the same distance and number of passengers, the GWP is 4.5% lower, releasing 260 g CO_2-eq.

Similarly, the life-cycle emissions of the electric and diesel cars used in Venadillo are also 4.5% lower than those of the same cars in Ibagué. Nevertheless, great differences can be noted when comparing the motorcycles from these two areas: electric and conventional scooters in Venadillo emit 34% less CO_2-eq than those in Ibagué. These differences are mainly due to the average occupancies of the analysed vehicles: the survey carried out in Venadillo gave occupancy ratios of 1.6 and 1.7 passengers per vehicle for automobiles and motorcycles, while the occupancies of Ibagué's cars and scooters were assumed to be 1.5 and 1.1. To make a general comparison of the two areas, weighted average emissions were calculated considering the fleet split of each setting: weighted average emissions from vehicles in the urban area are 140 g CO_2-eq·pkm^{-1} while those in the rural area are 19% lower, with a weighted average of 110 g CO_2-eq·pkm^{-1}.

If we compare the results shown in *Figure 6* with those from other studies, we can find striking similarities regarding the GWP of bicycles: the findings exposed by Philips et al. (2022) suggest that conventional bikes release 27% less carbon dioxide than electric bicycles, taking into account the life-cycle emissions gathered in *Table 2*. This is aligned to the estimation made in our study, since we found that conventional bikes have a reduction of 28% in life-cycle emissions when compared to electric bicycles, considering the results in *Figure 6*. By contrast, remarkable differences can be noted when analysing motorcycles: data showed by Veiga (2020) and Tuayharn et al. (2015) reveal potential reductions of 12% and 53% in life-cycle carbon emissions by using electric motorcycles instead of the conventional ones. Nonetheless, our results show a potential reduction that is even greater: for both of the areas analysed, electric scooters entail a CO_2-eq saving of 67% when compared to conventional motorcycles.

Regarding four-wheel vehicles, our estimations indicate that electric cars can reduce CO_2-eq by 62% and 66% when compared to diesel and petrol cars, respectively. This contrasts with the 17-

34% range of savings estimated by Zheng and Peng (2021). However, the good environmental performance of battery electric vehicles during their usage in Tolima might be due to the highly sustainable electricity generation process included in Ecoinvent 3.8 for the Colombian market, comprised of 83% renewable energy, most of which corresponds to hydro energy.

In this context, even a conventional scooter, which has a lower material consumption in its production and occupies less volume for distribution operations than a four-wheel vehicle, emits 6.3% more CO_2-eq than an electric car in Ibagué, as shown in *Figure 6*. In addition, it is worth noting that the conventional bike has the lowest level of CO_2-eq emissions, despite taking the consumption of calories in usage into account as an impact in the LCA.

It is also fair to state that diesel is a better fossil-based alternative over gasoline, since an average reduction of 11% has been detected when comparing life-cycle carbon emissions from diesel cars to those of petrol cars in both areas analysed. Nonetheless, the use of ICEVs should be discouraged since the combustion of fossil fuels in the transport sector leads to an aggravation of the air quality along city, roads and highways (Hooftman et al., 2016). In that sense, electrifying transportation and prioritizing the removal of carbon-fuel based combustion can be preferably suggested to consider air quality impacts in climate mitigation policies (Commane & Schiferl, 2022).

According to Liu et al. (2021), the service life is the main influencing factor on the emissions from road passenger vehicles. This is aligned to the results obtained for Ibagué: it is possible to affirm that 84% of GWP correspond to the use phase in petrol cars, with a similar tendency in diesel cars whose use phases have a contribution of 83% (Supporting Information Table S3). This emphasises the influence of fossil-related tailpipe emissions on the life-cycle impacts of ICEVs since, in BEVs, the contribution of usage decreases to 48%. However, in electric cars the phase of raw materials acquisition accounts for a notable proportion of life-cycle emissions, with a contribution to GWP of 39% which suggest that the improvement of efficiency in extraction and production processes should be prioritised in a city's target of vehicular electrification.

In this respect, Sofana et al. (2022) affirm that the automotive industry is currently in the middle of a revolutionary pathway towards cleaner energy on a global scale, with an increasing development of solutions for the problems faced in the field of electrification. Thus, Electric Vehicle (EV) manufacturing is reasonably expected to be more efficient in the near future, while the EV market is growing exponentially. In this sense, a sensitivity analysis has been performed as part of this research, in order to address the possibility of an increase in the environmental efficiency of EV manufacturing.

Figure 7 illustrates how the emissions of g CO_2-eq·pkm^{-1} from the electric cars in each area decreases, as EV manufacturing efficiency grows from 5 to 30%. This range was established taking into account that the carbon intensity of electricity generation worldwide is expected to fall up to 30% in the near term, which is likely to result in a reduction in GHG emissions related to the manufacture of EV components (European Environment Agency, 2018). For this sensitivity analysis, improvements in EV manufacturing were assumed to result in reductions in emissions related to the extraction of raw materials and production (Supporting Information Table S4). As it can be seen, a manufacture improvement that generates a 30% reduction in EV manufacturing emissions could reduce the GWP of the electric car by 12.6% in both areas.

Figure 7. Sensitivity analysis of EV Global Warming Potential with increases in EV manufacturing efficiency.

Similarly, the influence of hypothetical instances of EV market growth on the average GWP of private vehicles has been also estimated for each area. These episodes of growth were assumed to result in increases in the fleet size of electric automobiles and motorcycles up to 12%, which corresponds to the EV share of the European auto market in 2022 (European Commission, 2022) (Supporting Information Table S5). In this sense, *Figure 8* shows that a 12% growth in the fleet share of electric cars and scooters could reduce the average GWP by 22.1% in Ibagué and 23.8% in Venadillo.

Figure 8. Sensitivity analysis of average GWP with increases in the fleet size of electric vehicles.

The importance of exhaust emissions in two-wheel vehicles is also evident: the usage of conventional scooters represents 88% of life-cycle CO_2-eq emissions, while for e-scooters this percentage is barely 21%. This means that it is feasible to drastically reduce exhaust emissions in a city by promoting the use of renewable electricity-based propulsion systems in vehicles. Furthermore, the raw materials acquisition stage dominates the contributions to GWP in electric motorcycles, which highlights the importance of improving the manufacture of these vehicles on the road to transport electrification.

Regarding the life-cycle stages of bicycles, the usage of a conventional bike corresponds to 54% of its GWP, whereas this stage represents 26% of life-cycle carbon emissions in electric bikes. These contributions are due to the calorie consumption implied in pedaling since, naturally, the human energy required for using conventional bikes is higher than that for electric bicycles. With the aim of comparing the behaviour of each stage in urban and rural areas, weighted average contributions were calculated, taking into account the fleet size of transportation systems in each city. Then, we were able to see that, while the urban area shows higher contributions in stages such as distribution, usage, maintenance and final disposal, with increases of 0.040%, 0.90%, 0.30% and 0.10%, respectively; the rural area presents increments of 1.2% and 0.2% in the stages of acquisition of raw materials and production (Supporting Information Table S3).

6.8.2 Comparative of CO_2 emissions per day from available vehicles

In order to compare local tendencies in the passenger transport emissions of Ibagué and Venadillo, the per-person daily grams of emitted CO_2-eq were calculated by computing the results of the LCA with the average travelled distance and the average number of daily trips. Also, to address the differences between the environmental impacts of automobiles, motorcycles and bicycles, weighted averages of daily emissions have been calculated taking into account the fleet size of each vehicle category. To illustrate this procedure, *Table 7* shows these data and results for Ibagué:

Table 7. Total CO2 emissions from all vehicles analysed in Ibagué.

Vehicle	Global warming potential (gCO_2-eq·pkm^{-1})	Average distance travelled (km·$trip^{-1}$)	Average number of trips (trips·day^{-1})	Emissions per passenger in one day (g CO_2-eq·p^{-1}·day^{-1})	Weighted averages based on fleet sizes (g CO_2-eq·p^{-1}·day^{-1})
Petrol car	280	9.6	2.0	5,400	
Diesel car	250	9.6	2.0	4,800	5,400
Electric car	94	9.6	2.0	1,800	
Conventional scooter	100	8.7	1.1	950	950
Electric scooter	33	8.7	1.1	310	

Electric bike	21	6.2	0.4	51	40
Conventional bike	15	6.2	0.4	36	

Given these results, it is feasible to state that a vehicle's daily emissions have a strong dependence on the per-day trips made by its passengers. If we compare the weighted averages of the CO_2-eq·p^{-1}·day^{-1} released by each type of vehicle, it can be estimated that daily carbon emissions from automobiles are 460% higher than those from motorcycles. At the same time, the per-passenger daily emissions from bicycles are 96% lower than those from scooters. This has an explanation in that conventional scooters and petrol cars alone represent 97% of all trips made by individual and private transportation systems in Ibagué, due to the fleet of these vehicles being vastly higher than the rest: 89% of all private vehicles in the city correspond to conventional cars and motorcycles according to data referenced in *Section 2.1*.

These estimations could not be made the same way for Venadillo, due to the lack of available data about the vehicular census, average travelled distance, number of trips per day and average occupancy of vehicles for that area. Nonetheless, the applied survey allowed us to calculate these variables, as well as modal shares for fleet size estimation. In this context, *Table 8* shows the daily CO_2-eq emissions per passenger emitted by the private transportation systems of this setting:

Table 8. Total CO2 emissions from all vehicles analysed in Venadillo.

Vehicle	**Global warming potential (gCO_2-eq·pkm^{-1})**	**Average distance travelled (km·$trip^{-1}$)**	**Average number of trips (trips·day^{-1})**	**Emissions per passenger in one day (g CO_2-eq·p^{-1}·day^{-1})**	**Weighted averages based on fleet sizes (g CO_2-eq·p^{-1}·day^{-1})**
Petrol car	260	2.1	2.3	1300	1,200
Diesel car	240	2.0	2.0	940	
Electric car	90	0.0	0.0	0.0	
Conventional scooter	66	3.8	3.9	990	990
Electric scooter	22	0.0	0.0	0.0	
Electric bike	21	0.0	0.0	0.0	38
Conventional bike	15	1.1	2.2	38	

As it can be seen, the average number of daily trips also has a great influence on the per-passenger emissions from vehicles of Venadillo: despite the fact that conventional scooters have 72% lower per-passenger-kilometre emissions than diesel cars, their travelled distances and number of daily trips are considerably higher, resulting in 5.1% more CO_2-eq·p^{-1}·day^{-1}. Additionally, the fleets of cars and motorcycles are much higher than the rest of vehicles of Venadillo: 81% of the total private transportation systems correspond to these vehicles, which is a fleet share similar to that of Ibagué. Despite this, there are important differences in terms of daily emissions of CO_2-eq per passenger, as shown in *Figure 9*.

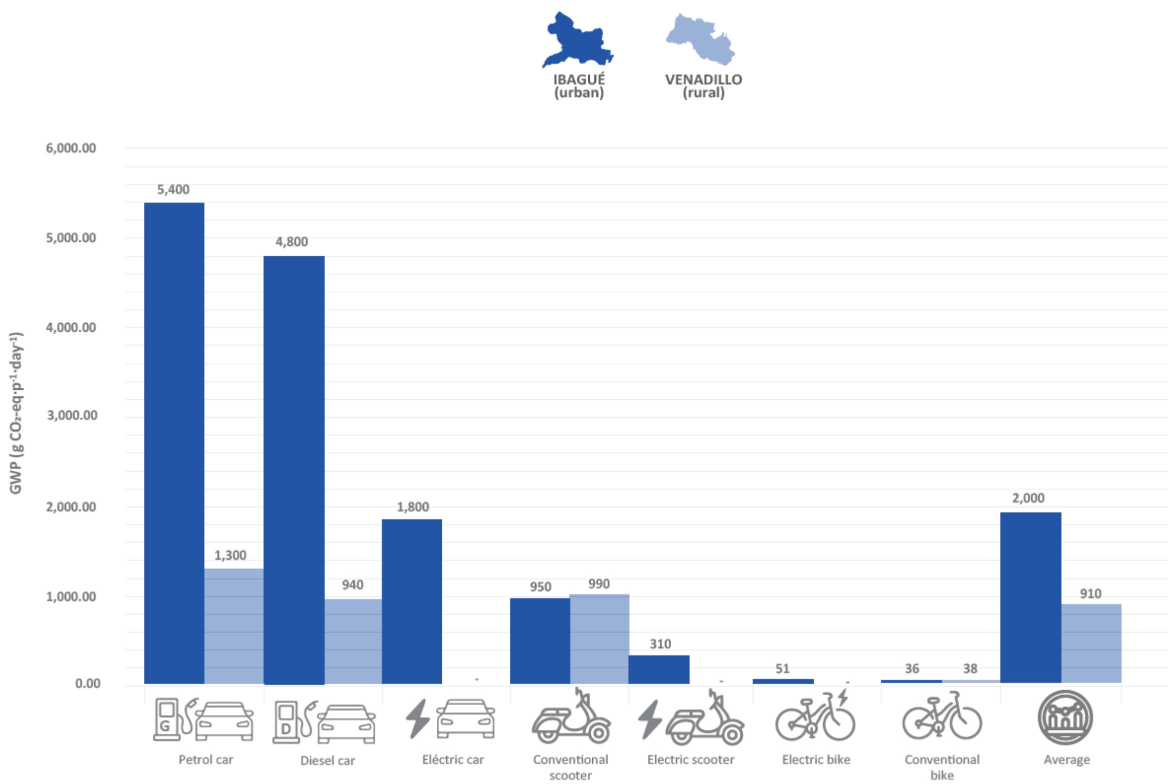

Figure 9. Comparative of total CO2 emissions per day of each transportation systems.

As can be seen, there is a clear difference between the daily CO_2-eq per passenger emitted by vehicles in Ibagué and those of transportation systems in Venadillo: based on weighted averages, it can be estimated that the urban transportation systems emit 120% more daily than those of the rural area. This is due to an extensive usage of traditional vehicles, with a low average occupancy and a high number of daily trips in the capital city of Tolima.

Several scenarios can be tested to improve the GWP of each transportation system analysed: increasing the average occupancy of vehicles and promoting shorter daily trips (Machado et al., 2018) are just a few examples that could be considered by local administrators, mobility policy designers or researchers for future projects. Also, carsharing services could be integrated to public transport, with a positive impact on GHG emissions, as inferred by Terrien et al. (2016). In this regard, investment in infrastructure for public transport should be prioritised in the target of correcting for drive excess in a city (Garcia-Sierra and van den Bergh, 2014).

6.9 Conclusions

Ibagué and Venadillo are sample areas of two different tendencies in mobility: an urban high-density population with an elevated level of vehicular traffic on the one hand, and a rural town with a low level of economic or industrial activity and a limited vehicular census on the other. As previously stated, the aim of comparing these areas was to identify the current environmental situation of individual transportation systems using an LCA-based vision and, consequently, to provide useful information for future projects that seek improvements in CO_2-eq emissions from the private vehicles used in each area. Thus, this study has allowed us to establish a concrete view of private mobility tendencies that can be useful for policy designers.

Regarding two-wheel vehicles, the use of e-scooters could be recommended over conventional ones in both analysed areas, insomuch as this could result in a 67% reduction in per passenger-kilometre CO_2 emissions. Nonetheless, there is a unique factor when comparing the conventional scooter and the electric car: in Ibagué, a conventional scooter emits more than an electric car, whereas, in Venadillo, conventional scooters are more sustainable than electric cars. This is due to the higher average occupancy of motorcycles estimated at 1.7 passengers for Venadillo, while an average of 1.1 was assumed for Ibagué. This sheds light on how not only the technology used can entail reductions but also the social behaviour that has been adopted.

Among four-wheel vehicles, the electric car is the most sustainable mode of transport in terms of CO_2-eq·pkm^{-1} emissions, with reductions in both areas of 66% and 62% when compared to petrol and diesel cars, respectively. It is worth noting that these reductions are expected to be even higher in the near term, since the GWP of the electric car may decrease by up to 12.6%, if the EV manufacturing efficiency is improved to reduce the carbon emissions related to the production processes, as shown in *Figure 7*. Similarly, shifting ICEV trips to EV may lead to a reduction in the average GWP by up to 22% in Ibagué and 24% in Venadillo, as suggests our sensitivity analysis about the potential increase in the EV fleet share. In this respect, implementing a 100% renewable mix energy in the market for electricity—instead of the current 83%—could be explored in the near future in order to boost vehicular electrification in both areas. To such purpose, policy makers should address the influence of the battery manufacturing on the life-cycle environmental impacts of EVs, with the aim of considering the additional energy consumption and GHG emissions implied in the production processes (Qiao et al., 2017).

Variables such as average distance travelled and number of daily trips have an important impact on GHG emissions in such a way that, if an analysis by transportation unit is performed, in terms of CO_2-eq·pkm^{-1}, Ibagué's emissions are only 23% higher than those of Venadillo. In contrast, if the aforementioned variables are taken into account, great differences come into view: the capital city of Tolima has CO_2-eq·p^{-1}·day^{-1} emissions 120% higher than those of Venadillo. This is due to the long trips made by citizens of Ibagué, on average 200% longer when compared with those of the analysed rural area (2.9 km in rural versus 8.7 km in urban).

In this study, we can conclude that the use phase of private transportation systems should be prioritised when modelling sustainable scenarios for each area, due to its high contribution to GWP, varying between 21% and 88%, with weighted averages of 83% and 82% for Ibagué and Venadillo, respectively. In this sense, proposals of low carbon scenarios for urban and rural areas should be focused on cars and motorcycles, on account of their high percentage in the vehicular census: 89% for Ibagué and 81% for Venadillo.

In this research we also conclude that, on average, conventional bicycles emit 94% less CO_2-eq·pkm^{-1} than petrol cars, and 77% less life-cycle carbon emissions than conventional scooters. This should be taken into account in the prioritisation of sustainable means of transport, especially in areas where the implementation of a public transport system is unfeasible due to the cost-benefit ratio or the characteristics of the region.

Finally, it is worth recalling that the modal share of private passenger transportation in Ibagué is 66%, according to the Consejo Nacional de Política Económica y Social (2020), for which reason it is pertinent to consider all transportation modes, including public ones, in order to address the current situation of mobility in the capital city of Tolima and model sustainable scenarios through future research oriented towards establishing a low-carbon and non-fossil fuel-based transportation tendency.

7. Towards sustainable passenger transport: carbon emission reduction scenarios for a medium-sized city

7. 2nd article: Towards sustainable passenger transport: carbon emission reduction scenarios for a medium-sized city

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7.1. Conflicts of interest

The authors declare no competing financial interest.

7.2. Acknowledgements

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7.3 Highlights

- Eight scenarios for reducing emissions from passenger transport are tested.
- A life-cycle perspective is applied to design scenarios with comparative measures.
- Real parameters affecting the mobility in a medium-sized city are addressed.
- Reducing mobility shows to be the most sustainable measure for emission mitigation.
- Realistic conditions to reduce emissions by enhancing public transport are provided.

7.4 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.

Keywords: transportation systems, life-cycle assessment, greenhouse gas emissions, decarbonisation, global warming.

7.5 Graphical Abstract

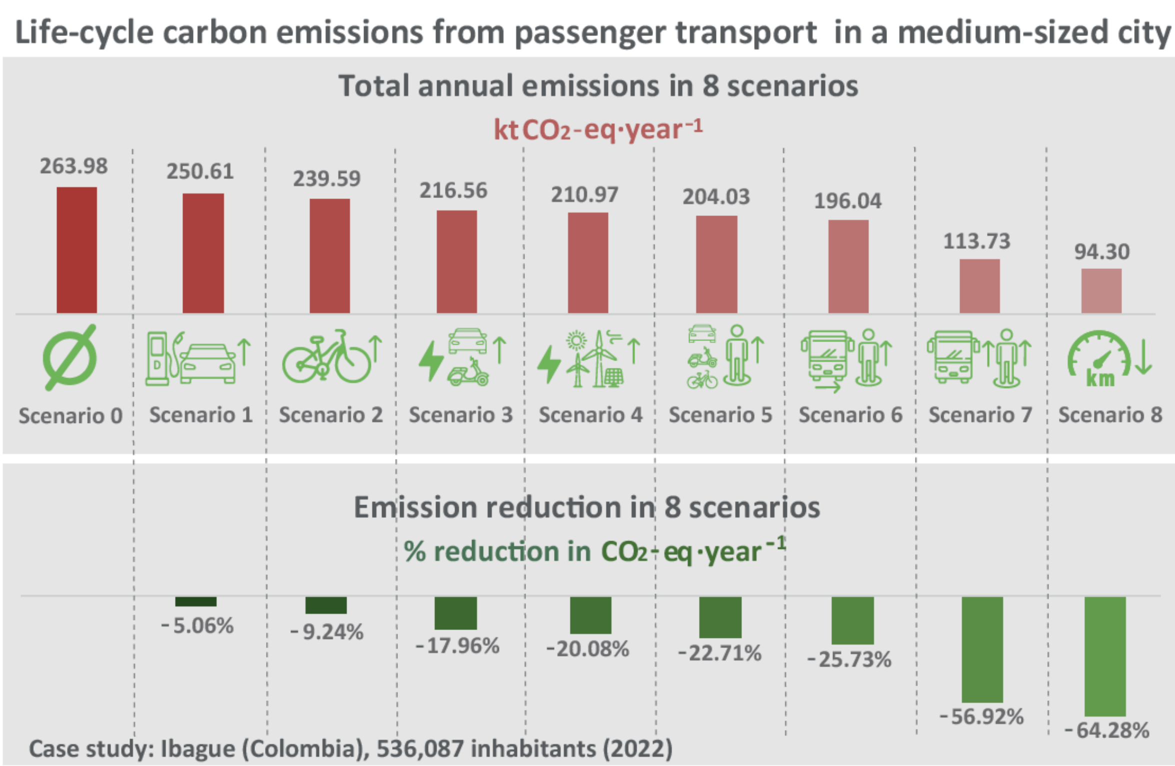

Figure 10. Graphical abstract for the third paper

7.6 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

7.7. 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 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 $CO_2\text{-eq}\cdot\text{pkm}^{-1}$, 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 9. 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)

Table 9 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).

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 minutes 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.

7.8. 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.

7.8.1 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 10* 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).

Table 10. 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		61,673	9.64	2.01
Diesel car	392	11.60%	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	4,888	1%	1,250	6.20	0.39
Conventional bike	16,083		4,111	6.20	0.39
Public buses	774	34%	182,269.57	9.15	1.71

7.8.2 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 11* 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.

Table 11. 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	1,387 km	1 passenger
Electric bike	China	19,064 km	15,000 km	1,387 km	1 passenger
Bus	Sweden	19,538.82 km	1,373,912 km	68,695.60 km	12 passengers

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 11*, the distance from the production point to Ibagué includes trips by sea (SeaRates, 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 (Universidad de 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. 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.

7.8.3 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 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).

7.8.4 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.

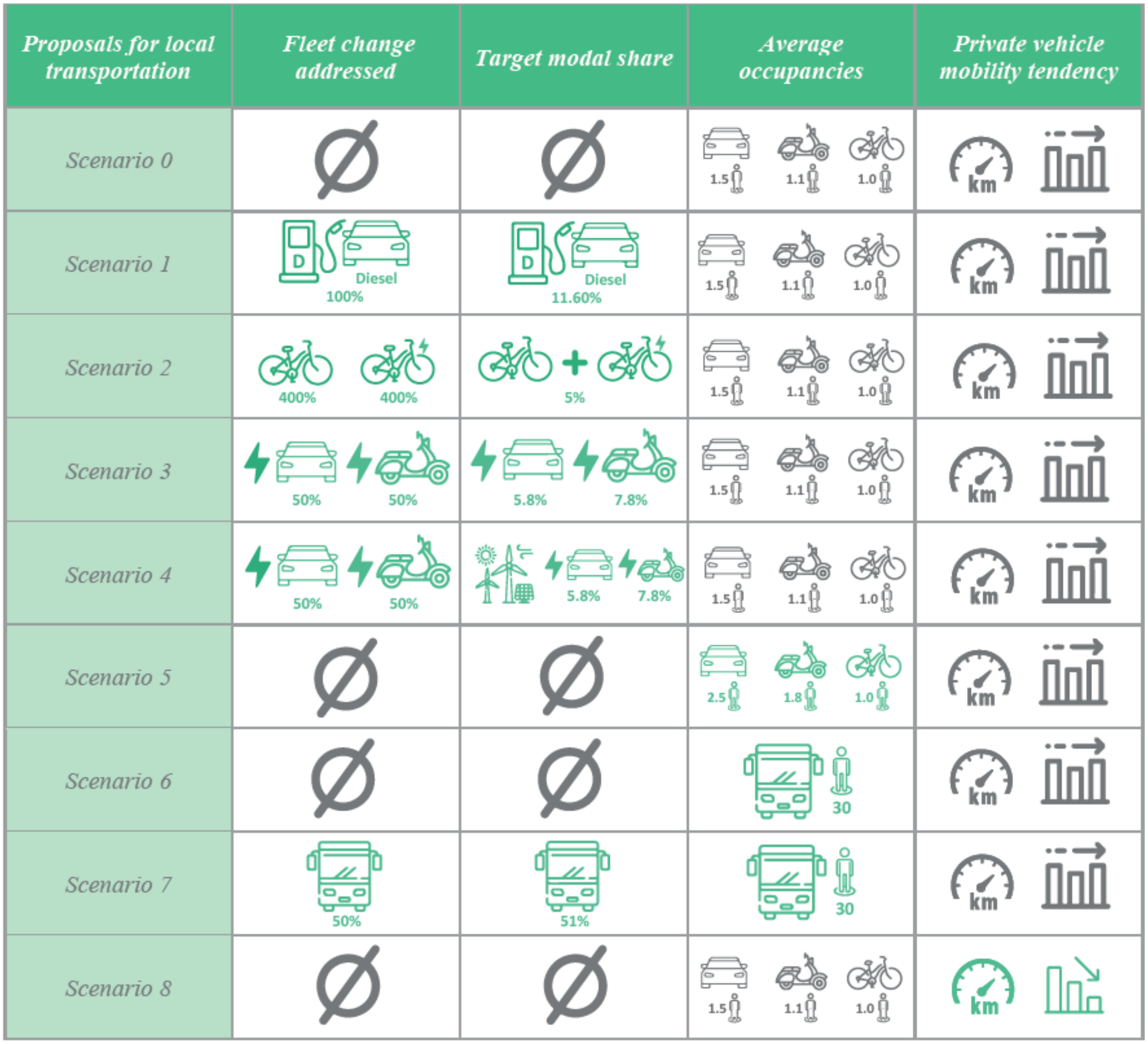

Figure 11. Depiction of proposed scenarios.

Figure 11 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 Figure 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 12 shows the mean characteristics of each scenario proposed for the selected city, according to descriptions previously provided (Supporting Information Table S5).

Table 12. 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	4,888	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	4,888	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	4,888	16,083	1,161
Scenario 8	ADT (km·trip^{-1})	4.82	4.82	4.82	4.36	4.36	3.10	3.10	9.15
	Average of TpD (trps·day^{-1})	1.01	1.01	1.01	0.55	0.55	0.20	0.20	0.85

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 13)*.

Table 13. 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	5,361	23.31%	1,250	0.26	4,888

	Conv. Bike		76.69%	4,111	0.26	16,083
Collective (51%)	Buses	273,404	100%	273,404	235.49	1,161

7.9 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 14*, 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}.

Table 14. CO2-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 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 year 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 14*—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.

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 homeworking 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 *Figure 12*, 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.

Figure 12. Comparison of carbon emissions in the proposed scenarios.

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. *Figure 13* provides a comparison of reductions offered by each scenario.

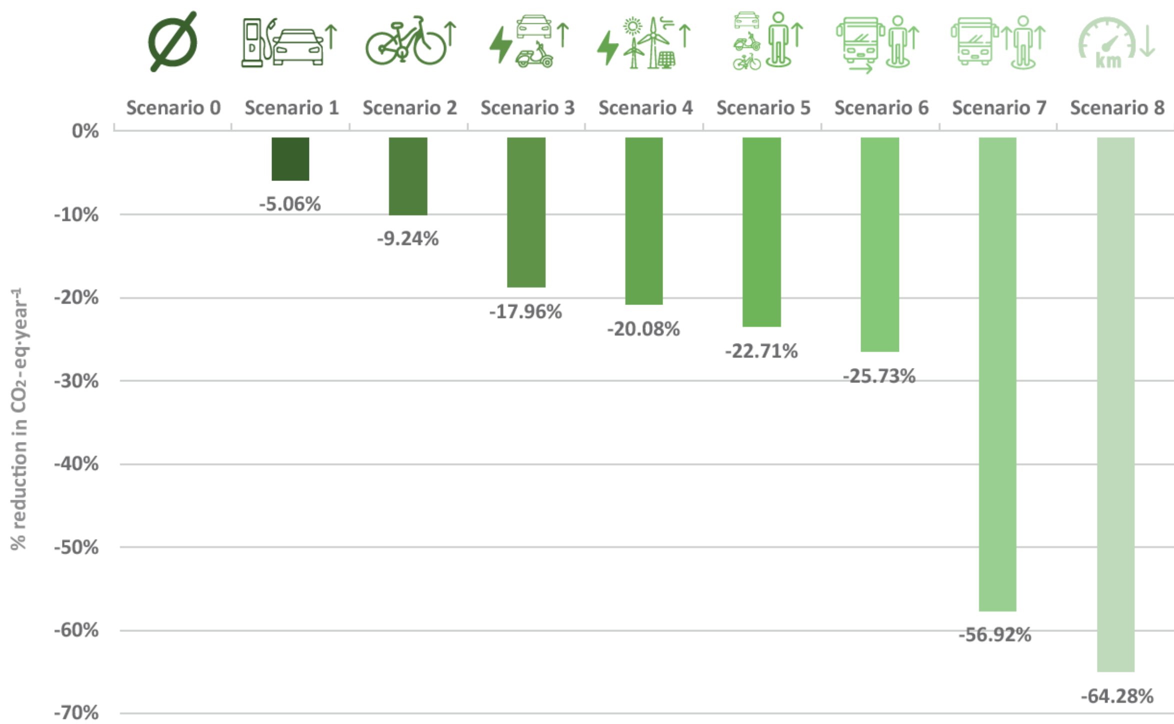

Figure 13. Comparison of carbon emission reductions in the proposed scenarios

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 9*, 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 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 *Figure 14* shows, our approach sheds light on how an increased bus 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.

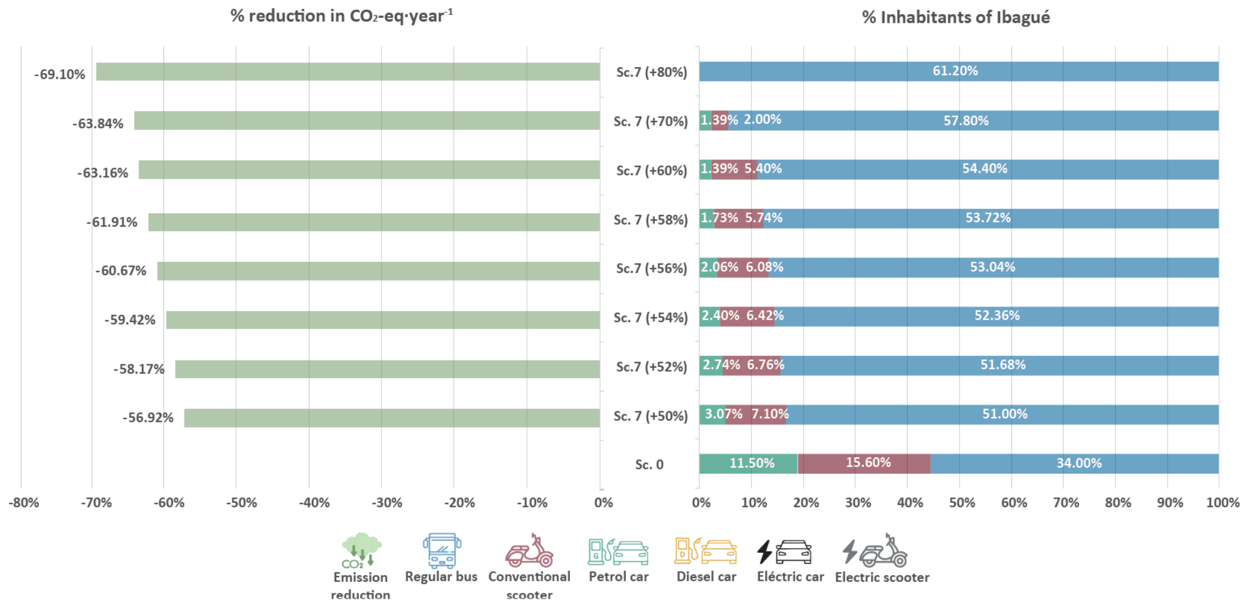

Figure 14. Emission reductions of Scenario 7 with several fleet increases.

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.

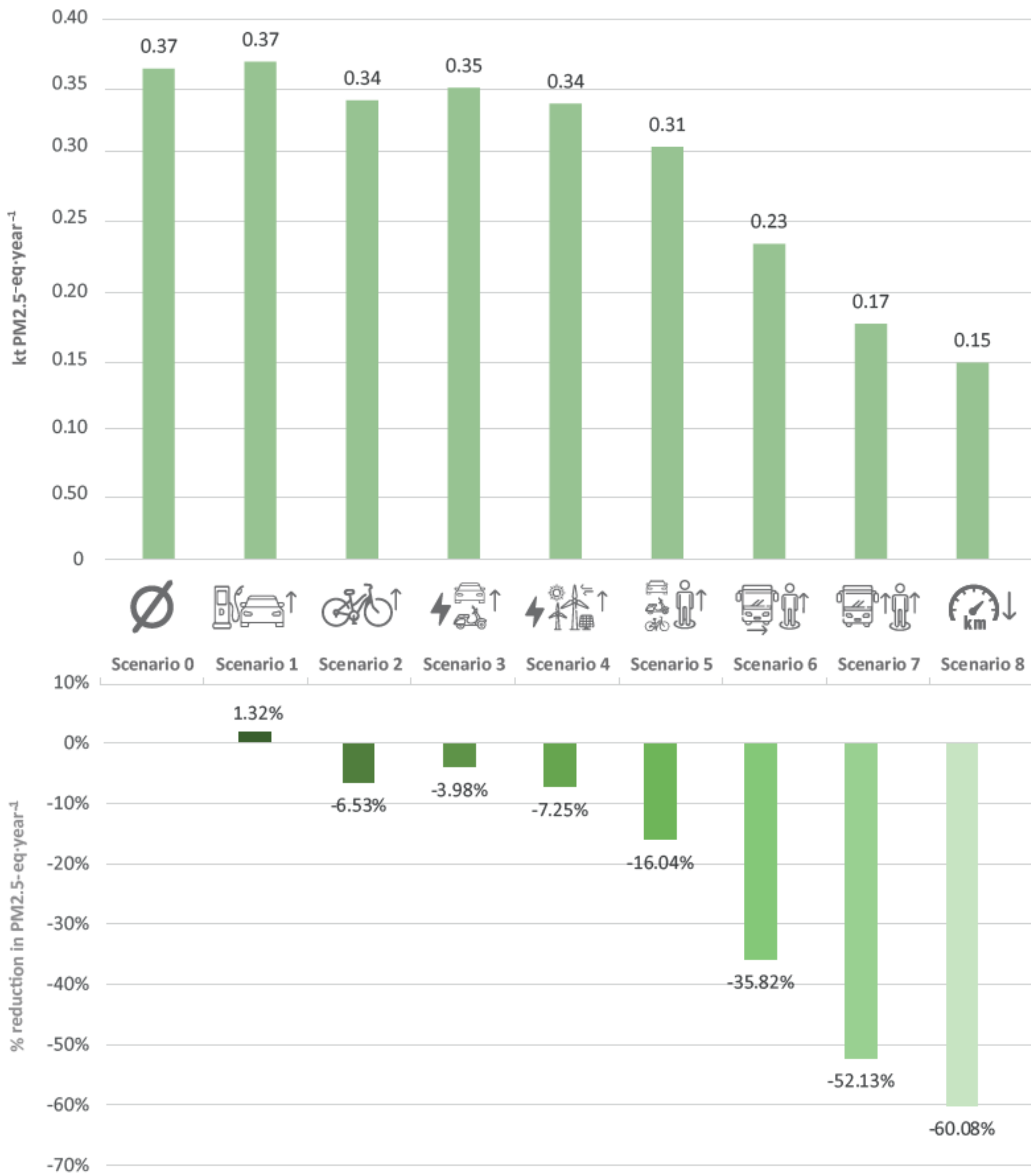

Figure 15. Comparison of emissions of PM2.5 in the simulated scenarios.

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.

Figure 16. Comparison of cumulative energy demand in the simulated scenarios.

Despite the fact that the use of diesel cars is associated with increasing PM2.5 emissions, as shown in *Figure 15*, 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 *Figure 16*. 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.

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 & 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.

7.10 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 10* 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 *Figure 13* 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.

8. Optimal replacement scenarios for an average petrol passenger car using life-cycle assessment

8. 3rd article: Optimal replacement scenarios for an average petrol passenger car using life-cycle assessment

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8.1. Conflicts of interest

The authors declare no competing financial interest.

8.2. Acknowledgements

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8.3 Highlights

- This study offers insights on the environmentally optimal time to replace an old car.
- Impacts of car replacement were analysed through Life-Cycle Assessments.
- Considering carbon emissions, electric cars serve as substitutes after 8.88 years
- Using renewable energy for the new electric car could shorten the substitution time.
- Considering particulate matter formation, electric cars do not serve as substitutes.

8.4 Abstract

The reduction of the lifetime of vehicles, using scrappage schemes, has been identified as a transformation pathway in the target of reducing the environmental impacts of passenger transport. The energy-efficiency of manufacturing new automobiles needs to be measured in order to achieve environmental benefits when replacing old cars. Thus, the goal of the present study is to establish the environmentally optimal time in which to replace a petrol car, in five substitution scenarios that include a newer version of this car, a diesel car and an electric car. The average occupancy, annual mileage and the energy mix on the market for electricity were addressed in this approach. This research quantifies the GHG emissions from the selected vehicles, with the aim of determining the optimal number of years after which substitution should take place, by way of a novel contribution to the current literature. The results show that the base vehicle can be efficiently replaced after 8.88 years if an electric car is selected as the substitute. However, this period would decrease to 6.55 years if the new vehicle were powered with 100 % renewable energy. Moreover, an environmentally optimal replacement could be made at 3.29 years, if the substitute were an

electric car run with an average occupancy of 3 passengers and a 100 % renewable energy mix. It was also demonstrated that the EURO 5 diesel car could be a replacement option for the base vehicle after 13.65 years, considering GWP impacts exclusively. By contrast, there are no environmental benefits related to diesel cars when considering PM2.5 emissions, hence they are not a feasible environmentally optimal substitution. This article concludes that the substitution could be up to 69.94 % sooner if a cleaner energy mix is used to run the replacement car.

Keywords: internal combustion engine vehicle, battery electric vehicle, optimal environmental lifetime, life-cycle assessment, global warming potential.

8.5 Graphical Abstract

Figure 17. Graphical abstract for the fourth paper

8.6 Introduction

In order to prevent a global temperature rise of more than 1.5 ºC by 2030, transportation emissions must decrease by 50 %, while mobility demand is expected to grow by 70 % in the same period (World Economic Forum, 2021). Against this backdrop, vehicle replacement is generally seen as a logical response to environmental concerns about the air pollution and Greenhouse Gas (GHG) emissions associated with old cars (Marin and Zoboli, 2020), given that about 17 % of the oldest vehicles addressed in a case study in the United States contributed to 50 % of total fleet mass emissions, as shown by Bernard et al. (2020) in their research on emission share by vehicle age.

For instance, EURO 3 petrol cars have been found to be highly pollutant when compared to newer four-wheel vehicles. Bearing in mind the emission limits established for passenger vehicles by European Union legislation, Tanaka et al. (2012) show that EURO 3 petrol cars emit 3.59 %, 7.45 % and 44.17 % more CO_2 per travelled kilometre than EURO 4, EURO 5 and EURO 6 petrol cars, respectively. EURO 3 petrol cars were also found to be 25.36 %, 26.28 % and 60.19 % more pollutant than EURO 4, EURO 5 and EURO 6 diesel cars during use phase (Tanaka et al., 2012).

Data provided by Jaworski et al. (2019) suggest that the carbon emissions from EURO 3 petrol cars are about 28.2 % and 33.33 % higher than those from EURO 6 petrol cars for driving cycles in rural and urban areas, respectively. Meanwhile, if the vehicles are driven on motorways, the emissions from EURO 3 petrol cars are found to be 35 % higher than those from EURO 6 petrol cars.

To address the environmental impacts of older cars, several countries have implemented scrappage schemes with the aim of accelerating the adoption of cleaner vehicles, by taking old vehicles out of the fleet, while boosting the vehicle industry (Messagie et al., 2012). Nonetheless, these measures have been found to be very costly, and their efficiency depends greatly on the long-term use of the new cars, so that CO_2 emissions would only decrease if the new vehicles are kept in use for at least 4.7 years. This is reflected in a Japanese case study which showed that the first year of the scrappage scheme could actually increase the amount of life-cycle CO_2 emissions by about 3.5 million tons CO_2-eq (Kagawa et al., 2013).

Meanwhile, a study carried out by Jiménez et al. (2016) showed that there were no environmental benefits related to a scrappage scheme in Spain, given that its capacity to create new demand for more energy-efficient vehicles was found to be about 20 %, while the percentage required to make this measure environmentally beneficial from a perspective of Public Administration is estimated to be 30 %. The study also showed that, when an econometric perspective is applied to assess the actual impact of the measure, the scheme would not cause any significant increase in vehicle sales.

Life-Cycle Assessment (LCA) in combination with economic analysis is now understood as necessary in order to improve decision-making and establish efficient strategies for the new challenges related to the carbon footprints of the current automotive industry and the environmental impacts of passenger transport (Folęga and Burchart-Korol, 2017). Optimising the lifetime of vehicles and ensuring their efficient usage have been identified as key transformation pathways towards reducing the emissions associated with private transportation, given that these measures can reduce vehicles' life-cycle emissions by up to 35 % (World Economic Forum, 2021).

Furthermore, the European Union has set the goal of preventing waste generation by promoting long-lasting products (European Commission, 2015). However, the problem with this approach is the possibility of disregarding consumed energy and impacts from usage. Moreover, increasing a product's lifetime does not guarantee a reduction in environmental impacts, since older and less efficient products may generate higher impacts in extended usage than newer options (Hummen & Desing, 2021).

Meanwhile, the adoption of Battery Electric Vehicles (BEVs) is generally seen as a positive alternative that can help reduce environmental impacts compared to traditional Internal Combustion Engine Vehicles (ICEVs). According to Choma and Ugaya (2017), an average ICEV has a Global Warming Potential (GWP) of 124 g CO_2-eq·pkm^{-1}, while the carbon emissions per passenger-kilometre emitted by a BEV are 45.97 % lower. Nonetheless, the benefits related to BEVs are heavily reliant on the type of electricity source used to power them, since vehicle usage accounts for 70–80 % of the overall emissions if a mix heavily dependent on fossil energy sources is used, whereas the production phase is the most significant for overall emissions (70–75 %) if an electricity mix with lower GHG emissions is used (Faria et al., 2013).

Studies such as that carried out by Montoya et al. (2023) have compared life-cycle carbon emissions from ICEVs and BEVs in Colombian rural and urban areas. It compared the GWP of petrol, diesel and electric passenger cars and found that the analysed electric car, powered with the current Colombian energy mix (83 % renewable of which 93 % comes from hydro), emits 62 % less CO_2-eq·pkm^{-1} than diesel cars and 66 % less than petrol cars. Also, the World Economic Forum (2021) has revealed that ICEVs emit 147 g CO_2-eq per passenger-kilometre, while BEVs release 8.84 % less (134 g CO_2-eq·pkm^{-1}). This estimation took all stages of the vehicle's life-cycle into account and included repair components for a mileage of 200,000 km and an average occupancy of 1.5 passengers in hatchback models. Furthermore, if decarbonised energy is consumed in the use phase, a BEV only emits 44 g CO_2-eq·pkm^{-1} which means a 70.07 % reduction compared to ICEVs.

In a comparison of LCA results for various types of BEV and ICEV obtained in European case studies, Verma et al. (2022) show figures that indicate emission reductions of 36.45-39.44 % when analysing the GWP of electric cars versus that of conventional vehicles, using a cradle-to-grave approach. In contrast, if a wheel-to-wheel approach is applied, BEVs have a potential carbon emissions reduction in the range of 15.38-26.67 %. Another review of the LCA of electric vehicles carried out by Xia and Li (2022) shows that, assuming a lifespan of 150,000 km and using the current European power mix, the GWP of BEVs is reduced by 10-24 % compared to petrol and diesel cars. Also, Puig-Samper Naranjo et al. (2021) found that the life-cycle CO_2-eq emissions of BEVs in Spain are 48 % lower than those of petrol ICEVs.

According to Pipitone et al. (2021), electric cars release 73.04 g of carbon emissions per passenger-kilometre, which means a reduction of 55.81 % when compared to diesel cars, taking into account their Global Warming Potential of 165.27 g CO_2-eq·pkm^{-1}, as shown by Barbarias García (2018). Nonetheless, lithium-ion batteries used in BEVs have economic and practical challenges that make their recycling processes difficult, which suggests a potential inconsistency among the objectives of vehicular electrification and the target of achieving GWP reductions (Picard and Danthinne, 2022). In particular, the lack of legal provisions for batteries and weak extended producer responsibility could discredit vehicular electrification as a strategy to address global warming.

Regarding political efforts related to vehicular electrification, it is worth highlighting the research carried out by Broadbent et al. (2018), which summarised the effectiveness of measures adopted in the European Union to boost BEV uptake. For instance, in countries such as Norway, exemptions have been applied to the 25 % vehicle purchase tax, combined with support for the deployment of a recharge infrastructure, including fast chargers every 50 km on highways. As a result, the BEV market share in the Norwegian annual total of new cars increased from 6 % in

2013 to 29.04 % in 2016, making it the most successful market in that period, with the Netherlands following closely behind. Nonetheless, in 2015, other countries, such as China, France, and the United States, offered as many financial incentives as the Netherlands, but did not have the same success in encouraging BEV uptake. This study also showed that, in the case of the United Kingdom (UK), financial incentives have not necessarily succeeded in encouraging BEV purchase: in 2015, UK uptake (1.1 %) was lower than in Sweden (2.5 %), despite UK incentives being higher. They point out that despite the increase in recharge infrastructure investment, issues such as the low availability of chargers may discourage the acceptance of electric vehicles, since 23 % of chargers were unable to be used in 2015.

In addition, Kley et al. (2012) have explained that the difference in ICE and BEV taxation, expressed as a discounted number of incentives granted by the government to EV owners, and based either on the taxation scheme in place or special subsidies, is known as ‘absolute taxation incentives’. They explained that countries such as the UK, Norway, Denmark, Belgium and Spain have absolute taxation incentives ranging from 7,000 to 14,000 euros, including benefits such as a reduced sales tax and reduced annual vehicle tax. Their study also showed that Spain is among the countries whose BEV support schemes are based on incentives on capital expenditure ranging from 4,000 to 9,000 euros. Nonetheless, there is a current need for data regarding the real effectiveness and impact of these measures on vehicular electrification, in comparison with the likely advantages of lifetime optimisation.

In line with this, Ardente and Mathieux (2014) assessed the durability of energy-using products with the aim of measuring the potential benefits of lifetime extension as compared with those of substitution with better performing alternatives. This research found there to be significant life-cycle environmental benefits of extending the lifetime of certain products, but that this generally depends on the impact category, the repair processes and the efficiency of the replacement product. They concluded that this kind of assessment is suitable for product groups characterised by rapid technological change, which they illustrated by testing this method on washing machines. Thus, it is pertinent to address the specific conditions of the automotive sector in order to establish an optimum vehicular lifespan.

According to Bakker et al. (2014), life extension is a priority strategy in order to optimise the environmental performance of energy-using products, but one that has an important drawback in that there is a lack of developed knowledge about long-lasting product design. Despite this, several studies have addressed the connection between environmental impacts and the lifetime of automotive products. Petrović et al. (2020) showed that if the electricity production has an emission factor that approximates 400 g CO_2 per kWh, such as in countries of the European Union, petrol and diesel cars can be replaced with an electric car after 4.3 and 8 years, respectively. They used a life-cycle perspective to demonstrate that a 50 % lower emission factor in the electricity production could shorten the environmentally optimal time to choose an electric vehicle as a substitute to 3.2 and 4.8 years for petrol and diesel cars, respectively.

However, these estimations do not consider the EURO emission standard of the analysed vehicles, and thus do not discuss broader replacement options, since they use a general approach without a specific degradation rate nor a comparative analysis of emission savings. Suggested optimal lifetimes of vehicles have been better reported, but there is a gap of knowledge regarding the emission savings ratio and the environmental performance of the substitution options.

The goal of the present study is to establish the environmentally optimal time within which to replace a petrol car, using a life-cycle perspective to analyse the impacts of the substitution options, as well as shed light on the emission savings needed for environmental benefits to be reaped from scrappage schemes. Five scenarios have been modelled, using a EURO 5 petrol car, a EURO 5 diesel car, and an electric car with different energy mixes, as substitutes for the base vehicle. Usage conditions such as average occupancy, annual mileage and the energy mix on the market for electricity were also addressed in order to analyse the environmental performance of the replacement options. This research quantifies the GHG emissions of the selected vehicles, with the aim of setting a definitive substitution year, by way of a novel contribution.

This manuscript will first describe how LCA was used for the estimation of the Embodied Carbon (EC), which includes the impacts of the manufacture and end-of-life phases, and the Operational Carbon (OC), which represents the usage emissions of the selected automobiles. The results and discussion chapter shows the comparison of the life-cycle carbon emissions of the vehicles analysed, the results of the emission savings ratio associated with the substitution vehicles and the replacement year in each simulated scenario. Lastly, the conclusions describe how this work represents the first effort to provide an environmentally optimal replacement year for ICEVs, using a life-cycle perspective.

8.7 Methodology

For the purpose of analysing the environmental benefits associated with each substitution scenario, the GHG emissions of four types of vehicles were calculated by means of LCA. The EURO emission standard was taken into account for the selection of the vehicles that comprise the scenarios designed. Impact categories such as GWP and particulate matter formation were taken into account in order to observe how the replacement year and the environmental efficiency of the substitution vehicles are influenced by the decarbonisation strategy’s approach, as well as whether carbon emissions or air quality is being prioritised. In this chapter, the scope and the assumptions for the LCA are explained. Then, the parameters considered in the estimation of the vehicles' environmental impacts are described. Finally, the characteristics of the proposed substitution scenarios for the base vehicle are given.

8.7.1 Scope and assumptions

The LCA carried out in this research considered the environmental loads of life-cycle phases such as extraction of raw materials, manufacture, usage, maintenance and end-of-life (Supporting Information Figure S1). The energy and flows associated with distribution, from the vehicle factory to the place of use, were not included in the analysis. The functional unit for the carbon emissions calculation was one passenger-kilometre (pkm), so that the initial results were obtained by dividing (1) the GHG emitted by the vehicles per kilometre travelled, by (2) the European average occupancy of automobiles shown in *Table 15*, in accordance with the European Parliament (2019).

In order to analyse the environmental performance of the selected vehicles during their service life, the aforementioned results were multiplied by a lifetime performance of 320,000 pkm, which was calculated by assuming a maximum lifespan of 200,000 km and taking into account the average occupancy shown in *Table 15*. Also, an annual mileage of 12,562.9 km was established based on the Spanish average obtained from the National Institute of Statistics (2008). Thus, the lifetime of all analysed vehicles was estimated at 15.92 years.

As can be seen, the parameters considered for this approach are based on statistical reports from public organisations, hence they correspond to secondary data as well as the life-cycle inventories that, in this case, come from the version 3.9 of the Ecoinvent database. *Table 15* provides the main characteristics of the automobiles selected for the base case and the substitution scenarios.

Table 15. Summary of characteristics of the selected vehicles.

Vehicle	Size	European emission standard	Weight	Lifetime performance	Average occupancy
Petrol car	Small	EURO 3	1,200 kg	320,000 pkm	1,6 passengers
Petrol car	Small	EURO 5	1,200 kg	320,000 pkm	1,6 passengers
Diesel car	Small	EURO 5	1,200 kg	320,000 pkm	1,6 passengers
Electric car run with Spain's current energy mix	Small	-	1,180.22 kg	320,000 pkm	1,6 passengers
Electric car run with a 100 % renewable energy mix	Small	-	1,180.22 kg	320,000 pkm	1,6 passengers
Electric car run with a 100 % renewable energy mix	Small	-	1,180.22 kg	320,000 pkm	3 passengers

In this study, indicators are calculated with the aim of comparing the environmental benefits of the use of an old car versus those of replacing it. To this end, it was assumed that the GHG emissions of the production and the final disposal of the substitute vehicle would be avoided by keeping the old car. Meanwhile, the result of subtracting the usage emissions of both cars is considered an emission saving in the case of replacing the base vehicle, given that the GWP associated with the use phase of the base vehicle is higher than that of all the substitution options, as can be seen in *Figure 19*.

8.7.2 Estimation of environmental impacts

In accordance with the guidelines described in ISO 14044 (International Organization for Standardization, 2006), the LCA performed in this research followed the stages of goal and scope definition, inventory, impact assessment and result interpretation. Despite there being no Product Category Rules (PCR) for passenger cars available, as they are currently under development, this study included the functional units and system boundaries for passenger road vehicles, as suggested in PCR 2016:04 for the assessment of the environmental performance of public and private passenger buses and coaches, published by EPD International AB (2022).

ReCiPe 2016 v.1.01 was the selected method for the stage of impact assessment, which was performed using a Hierarchist (H) perspective, given that it is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms (National Institute for Public Health and the Environment, 2017). Characterisation factors at Midpoint level were used in this study, considering their connection with the impact categories and low calculation uncertainty (Bartek et al., 2021).

8.7.3 Designed scenarios

For the analysis, it has been assumed that the base scenario (Scenario 0) corresponds to a 1,200 kg EURO 3 petrol car used in Europe. This vehicle is the oldest version of petrol car available in the Ecoinvent 3.9 database. The life-cycle impacts for a lifetime performance of 320,000 km and an average occupancy of 1.6 passengers were considered for this Scenario, taking into account the European average occupancy of automobiles shown in *Table 15*. In order to estimate the optimal lifespan and the replacement year for the older vehicle in Scenario 0, five substitution scenarios were modelled calculating the carbon emissions associated with the newer options.

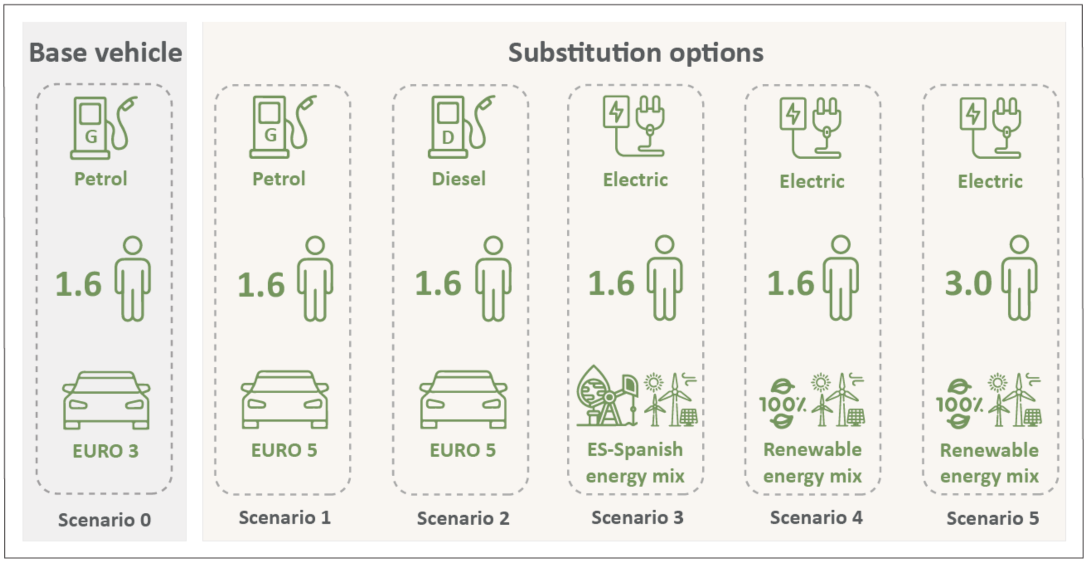

Figure 18. Description of the proposed scenarios with the substitution options.

In accordance with *Figure 18*, the substitution options correspond to the most recent versions of the petrol, diesel and electric cars available in Ecoinvent 3.9. Each vehicle was analysed by means of OpenLCA, a well-established carbon footprint assessment tool (Valls-Val and Bovea, 2022). The replacement scenarios are described below:

- Scenario 0 corresponds to the base vehicle: a small-sized EURO 3 petrol car run with an average occupancy of 1.6 passengers (Supporting information Table S1).

- Scenario 1 consists in replacing the base vehicle with a small-sized EURO 5 petrol car, taking into account the same usage conditions of Scenario 0 (Supporting information Table S2).

- Scenario 2 considers a small-sized EURO 5 diesel car as the replacement option for the selected vehicle, using the same lifetime performance and average occupancy of the base scenario (Supporting information Table S3).

- Scenario 3 considers a small-sized electric car (Supporting information Table S4) as the replacement option for the base vehicle, using electricity from Spain. The inventories included in Ecoinvent 3.9 indicate that the current energy mix from the Spanish market for electricity is comprised of 36.12% renewable energy (Supporting information Table S5). By way of reference, the global and European energy mixes are also tested in this scenario in order to assess the influence of electricity generation processes on the environmental performance of an electric vehicle.

- Scenario 4 is a complement to Scenario 3, with the same vehicle, but this time using a 100 % renewable energy mix in the Spanish market for electricity.

- Scenario 5 is a complement to Scenario 4, but this time using an average occupancy of 3 passengers in the replacement option.

In each scenario, a comparison is made between the potential emission savings associated with continuing to use the old car and those associated with the replacement option, in order to find the environmentally optimal ratio for the replacement of the old car. In this approach, the emissions from the manufacturing and end-of-life processes of the new car (Embodied Carbon $_{New}$) would be saved if the old car were used, instead of replacing it. In contrast, if the new car were used, the excess emissions from the old car would be saved (Emission savings in Operational Carbon $_{New}$). *Equation 1* expresses the ratio of emission savings associated with the vehicles in question, in accordance with the methodology based on the optimal operating periods of products proposed by Alejandre et al. (2022).

$$(1)\ Emissions\ savings\ ratio$$

$$= 100\ \% - \frac{Emodied\ Carbon\ (EC)_{New}}{Emissions\ savings\ in\ Operational\ Carbon\ (OC)_{\ New}}$$

For the present study, this equation was updated in order to assess the energy-efficiency of each alternative in terms of environmental benefits. The savings associated with the usage of the new car can be expressed as shown in *Equation 2* and *Equation 3.*

$$(2)\ Emission\ savings\ in\ Operational\ Carbon\ (OC)_{New}$$

$$= Operational\ Carbon\ (OC)_{Old} - Operational\ Carbon\ (OC)_{New}$$

$$(3)\ \sum_{yr=1}^{n} Emission\ savings\ in\ Operational\ Carbon\ (OC)_{New}$$

$$= Operational\ Carbon\ (OC)_{Old} - Operational\ Carbon\ (OC)_{New}$$

The production phase of the existing car was not taken into account for the calculation, since it is not feasible to eliminate the emissions that have already been released. Thus, the replacement year was estimated taking into account the emission savings ratio of each substitution option and the lifetime assumed for the analysed vehicle, by means of *Equation 4.*

$$(4)\ Replacement\ year = \frac{Embodied\ Carbon\ (EC)_{New}}{Emission\ savings\ in\ Operational\ Carbon\ (OC)_{\ New/year}}$$

8.8. Results and discussion

In accordance with the described methodology, this chapter shows the outcomes of the LCA performed on the vehicles selected for the base scenario and the substitution options. Firstly, the life-cycle emissions will be compared in order to comprehensively clarify the potential emission reduction of the replacement cars. Secondly, the results of the calculation of the emission savings ratios and the optimum replacement years will be displayed. Finally, the efficiency of the electric car using different energy mixes in the market for electricity will be analysed.

8.8.1 Comparison of the life-cycle emissions of the analysed vehicles

To estimate the optimal replacement year for the base vehicle, an LCA was performed which yielded the per passenger-kilometre carbon emissions of the vehicles in each scenario. The contributions to GWP were placed into two categories: (1) Embodied Carbon (EC), which includes the acquisition of raw materials, manufacture and end-of-life, and (2) Operational Carbon (OC), which corresponds to the use phase, including the maintenance of the automobile during its lifetime. *Figure 19* illustrates a comparison of the g CO_2 released by each vehicle and the contributions from the life-cycle stages (Supporting Information Table S6).

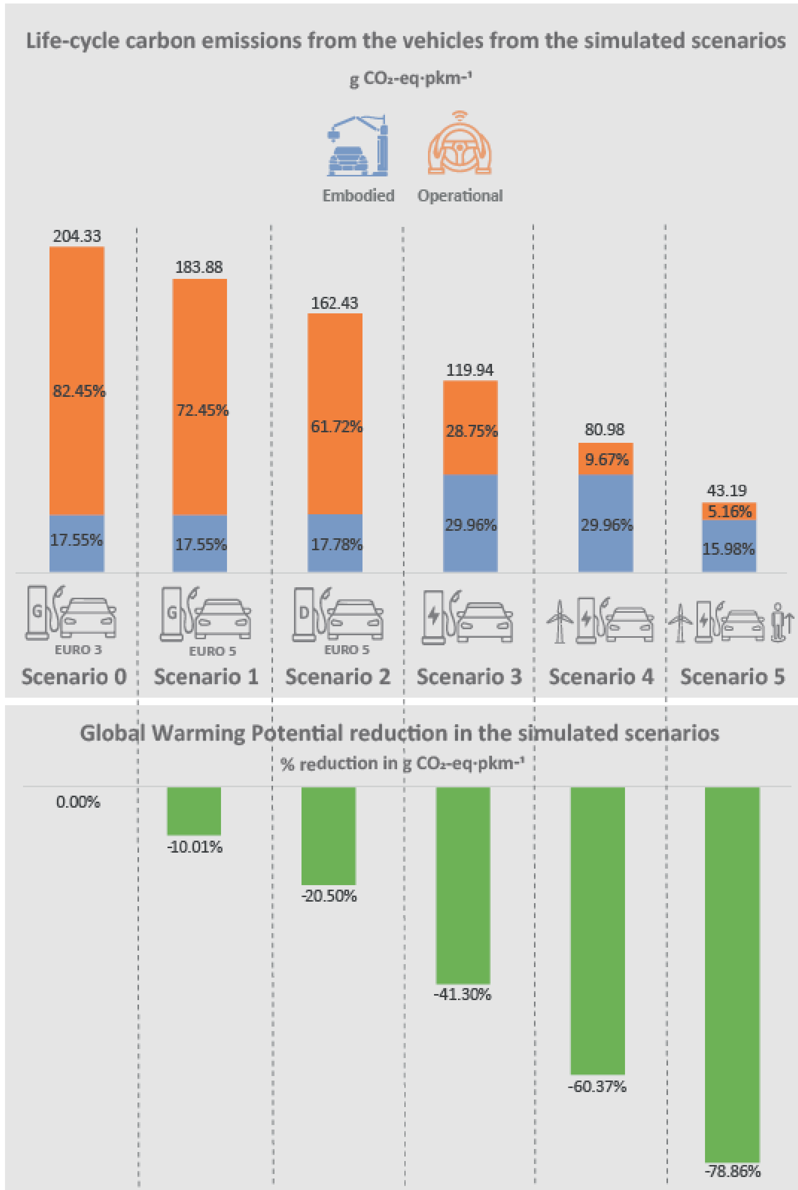

Figure 19. Comparison of the Global Warming Potential of the vehicles from each scenario.

The substitution options entail emission reductions in the range of 10.01 % to 78.86 % when compared to the base vehicle, with the most sustainable replacement alternative being the electric car if powered with 100 % renewable energy and run with an average occupancy of 3 passengers. In addition, the Cumulative Energy Demand (CED) associated with the life-cycle of the substitution options is lower than that of the vehicle in Scenario 0, with reductions in the range of

9.42-72.42 % (Supporting Information Table S7). The use phase has the highest contribution to GWP in ICEVs—between 77.64 % and 82.45 %—while the production phase is responsible for the most carbon emissions in the case of BEVs, with contributions ranging from 51.03 % to 75.59 %. In addition to underlining the impact of fossil fuel combustion in the life-cycle emissions of conventional cars, these findings also reveal that BEV manufacturing efficiency should be coped in the near future, in order to address vehicular electrification as a strategy to mitigate climate change and global warming.

In this respect, Sharma and Kumar Tiwari (2022) state that limitations such as safety concerns, high costs and limited driving range have been progressively controlled by several technological advances in the BEV industry. These improvements have led to an increase in the reliability and affordability of electric cars, which is expected to boost consumer acceptance and enhance the industry's ability to produce BEVs on a massive scale. Thus, a sensitivity analysis was performed with the aim of addressing the potential increase in the manufacturing efficiency of electric vehicles (EVs). For such purpose, it was assumed that an improvement in EV manufacturing would result in reductions in the emissions associated with the acquisition of raw materials and the production process.

Figure 20. Sensitivity analysis of GWP in scenarios 3 and 4, with increases in BEV manufacturing efficiency.

Figure 20 shows the potential reductions in the GWP of the electric vehicles in Scenarios 3 and 4, related to hypothetical increases in BEV manufacturing efficiency, in the range of 2 % to 20 %. As can be seen, an improvement that reduces the carbon emissions associated with BEV production by 20 % can lead to a 10.21 % decrease in the GWP of an electric car; while a 15.12 % reduction can be achieved if the vehicle is powered with 100 % renewable energy.

8.8.2 Emission savings ratio and optimum replacement year in the simulated scenarios

Using *Equation 2*, the OC savings of replacing the base car were calculated for each scenario, so that they could be compared to the EC of the substitution option, as the latter were assumed to be the savings of continuing to use the base vehicle. Subsequently, *Equation 1* was applied with the purpose of simulating each scenario and observing the evolution of the emission savings ratio over time. *Figure 21* shows how this ratio increases as the years of usage go by.

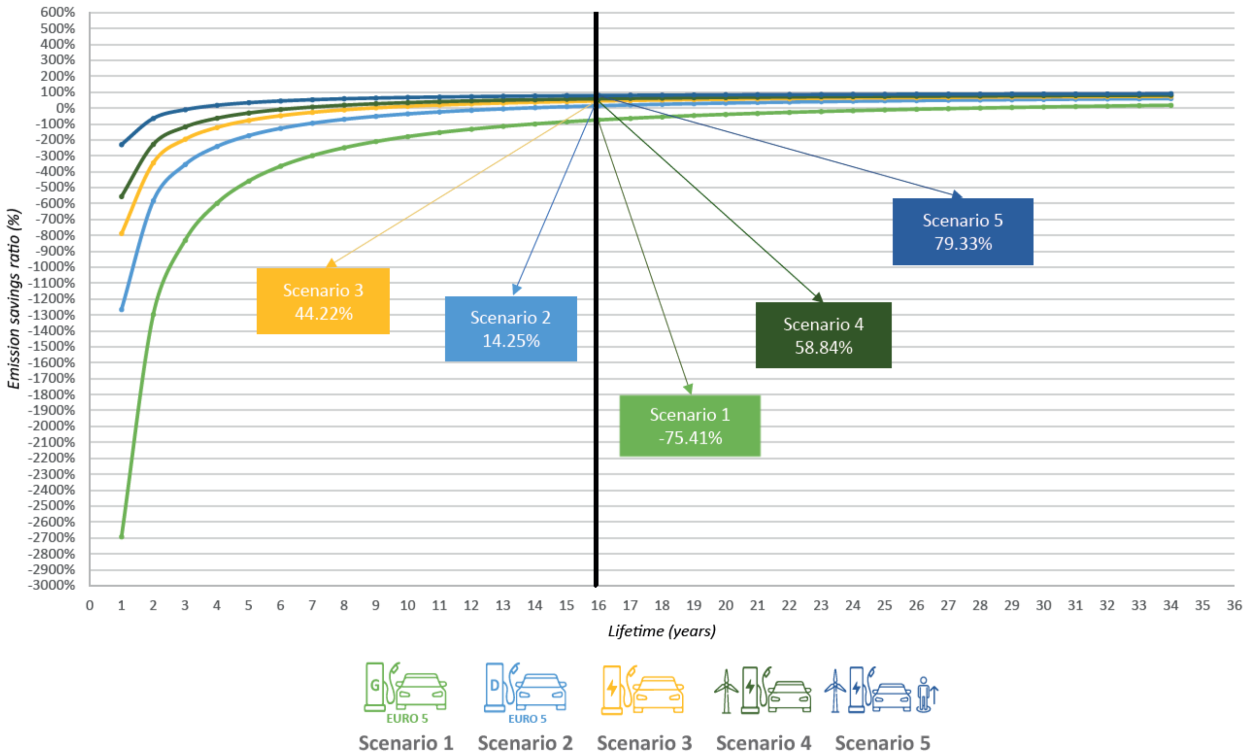

Figure 21. Emission savings ratio in the lifetime of the simulated scenarios.

As can be seen, by the end of the base vehicle's lifetime (15.92 years), the vehicle in Scenario 1 would still have a negative emission savings ratio, which means that the emissions associated with manufacturing the new car (EC) would be higher than the savings associated with using it. Therefore, it is not environmentally optimal to replace the base vehicle with a EURO 5 petrol car over the course of its lifespan. Meanwhile, the vehicle in Scenario 5 has the lowest emission savings ratio of all the simulated scenarios, at 15.92 years, which demonstrates that increasing the average occupancy and ensuring a renewable energy mix to power an electric car is the most sustainable measure by which to carry out an environmentally optimal replacement.

Table 16. GWP results and replacement year for the simulated scenarios.

Scenario	Description	Embodied Carbon (EC) g CO_2-eq	Operational Carbon (OC) g CO_2-eq	Emission savings in OC g CO_2-eq·pkm^{-1}	Total emission savings in OC g CO_2-eq	Savings ratio at end-of-life %	Year to replace
0	Base vehicle: EURO 3 petrol car	1.15E+07	5.39E+07	-	-	-	-
1	Replacing with a EURO 5 petrol car	1.15E+07	4.74E+07	20.44	6.54E+06	-75,41 %	27.93
2	Replacing with a EURO 5 diesel car	1.16E+07	4.04E+07	42.35	1.36E+07	14,25 %	13.65
3	Replacing with an electric car	1.96E+07	1.88E+07	109.73	3.51E+07	44,22 %	8.88
4	Replacing with an electric car using 100 % renewable energy	1.96E+07	6.33E+06	148.70	4.76E+07	58,84 %	6.55
5	Replacing with an electric car using 100 % renewable energy and 3 passengers	1.96E+07	6.33E+06	157.92	9.48E+07	79,33 %	3.29

Table 16 gathers the outcomes of the LCA performed on the selected vehicles (Supporting information Figure S2), in terms of total EC and OC. Also, the OC savings are shown in g CO_2-eq·pkm^{-1} and g CO_2-eq for the whole lifetime of the substitution options. The replacement year, calculated for each scenario by means of *Equation 4*, is also included. As can be seen, the electric car could be an environmentally optimal replacement for the base vehicle after 3.29 years, as long as it is used with an average occupancy of 3 passengers and powered with 100 % renewable energy from the Spanish electricity market. However, if the average occupancy were 1.6 passengers, the replacement year would go up to 6.55 years, while if the regular Spanish energy mix were used, it would be environmentally optimal to perform the replacement after 8.88 years.

Regarding ICEVs, a EURO 5 diesel car can also be a substitution option for the vehicle in Scenario 0 after 13.65 years, and could be recommended instead of the EURO 5 petrol car, since the optimal replacement time in Scenario 1 is 27.93 years, which is 1.75 times the estimated lifetime. Nonetheless, if the particulate matter impact category is selected as a criterion for the analysis, the differences are striking (Supporting Information Table S8): the automobiles in scenarios 2 and 3 would no longer be a substitution option for the base vehicle, as there would be no environmental savings associated with the new cars. Thus, the EURO 5 diesel car and the electric vehicle emit more ≤ 2.5 µm particles (PM2.5) than the EURO 3 petrol car. Also, the vehicles in scenarios 1, 4 and 5 would still have a negative emission savings ratio at the end of the estimated lifetime, so it is not environmentally optimal to make the substitution prior to 15.92 years.

Diesel cars also have an important drawback in that their life-cycle involves higher impacts in other environmental categories when compared to petrol cars. According to Puig-Samper Naranjo et al. (2021), the impacts of diesel ICEVs are higher than those of petrol cars in categories such as human carcinogenic toxicity, human non-carcinogenic toxicity and terrestrial, freshwater and marine ecotoxicity; with increases of 6.82 %, 7.23 %, 3.93 %, 8.99 % and 8.15 %, respectively. Thus, the environmental efficiency of the substitution vehicle and the replacement year depend to a large extend on the impact category selected for the analysis, as well as whether GHG or air quality is prioritised, as can be seen when comparing the results here shown.

If the results gathered in *Table 16* are compared with those from other studies, it can be noted that the replacement years shown for scenarios 2 and 3 are aligned with the optimal range within which to replace an automobile; namely, 7–14 years, as stated by Kim et al. (2003). However, this range is focused on optimising the vehicle's service life, and does not consider the emissions from the substitution options nor the environmental efficiency of the replacement. Similarly, the optimal lifetime of 11.5 years reported by Dewulf and Duflou (2004) corresponds to an average vehicle with no powertrain specifications, and does not account for the savings associated with the substitution car nor show an exact replacement year for each alternative.

Thus, the replacement year could be significantly influenced by several factors such as technological improvements or potential industrial advances in terms of cleaner and more sustainable production affecting the substitution vehicle. For this reason, a sensitivity analysis has been carried out in order to examine how the final results of each simulated scenario change as the environmental efficiency of the production processes increases, so that replacement options become greener. These improvements were assumed to result in reductions in the GWP of the new vehicle of up to 14%, which is the maximum reduction obtained by the optimisation of vehicle components, as reported by Spreafico (2021).

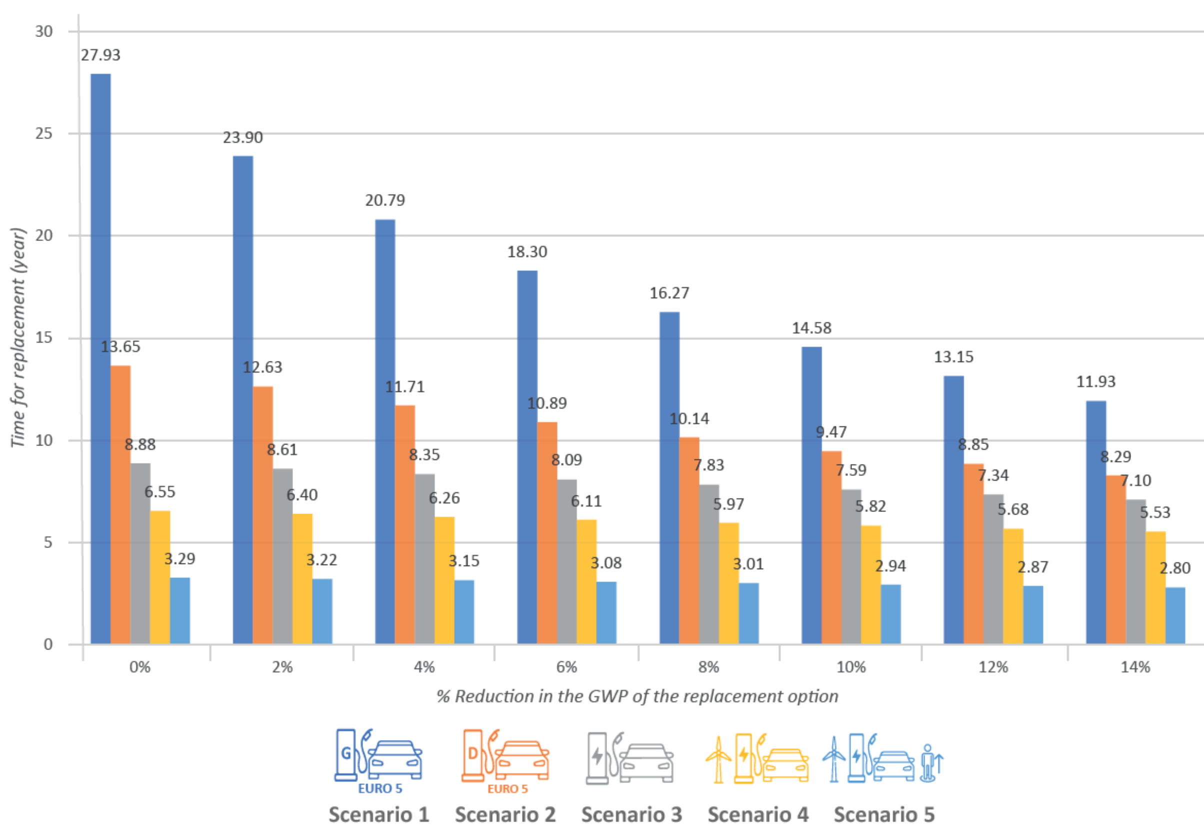

Figure 22. Sensitivity analysis of the replacement year, with reductions in the GWP due to component improvements.

Figure 22 shows that a technological improvement that yields a 14% reduction in the GWP of the substitution vehicle could reduce the time within which to replace the old car up to 2.80 years in Scenario 5, which means a decrease of 14.89% in the period initially estimated. Similarly, time reductions of 15.57% and 20.05% in scenarios 4 and 3 could also be achieved, in this particular case. However, the ICEVs are more sensitive to production improvements when considered as substitutes for the base vehicle, with replacement time reductions of 39.27% and 57.29% in the case of decreasing by 14% the GWP of the petrol and the diesel car, respectively.

In accordance with Spreafico et al. (2023), emerging technologies or industrial improvements require prospective LCA in order to assess their environmental sustainability. Patent analyses are now understood as necessary to meet the eco-designed solutions needed for reducing the carbon footprints of new products. In this respect, future research could address prospective LCA and patent analysis to comprehensively clarify the potential impacts of production improvements on the GWP of the replacement vehicles and their respective substitution period. In addition, a complete study could include other mobility strategies such as public transport renewal or district redesign for low-carbon transport.

8.8.3 Efficiency of the electric car using different energy mixes in the market for electricity

With the aim of demonstrating that the environmental performance of an electric car has a significant reliance on the energy mix used to power it, different electricity markets were tested to observe how the savings of using a BEV instead of the base vehicle change as the energy mix varies. For such purpose, Scenario 3 was modified in order to observe the evolution of the emission savings ratio over time, using an average occupancy of 1.6 passengers and the energy mix from Spain, Europe and the global average mix which are 19.35 %, 17.46 % and 11.43 % renewable, respectively. These percentages were obtained via the assessment method of Cumulative Energy Demand (CED), and in the case of Spain, the proportion of renewable energy yielded is striking since it differs from the percentage of sustainable electricity generation processes included in Ecoinvent 3.9 (36.12 %).

An additional simulation was performed with the aim of assessing the environmental benefits of replacing the base vehicle with an electric car run with marginal fossil electricity, which was assumed to come from coal, oil and natural gas (Giuntoli et al., 2017). This scenario was modelled by modifying the Spanish energy mix in order to examine the variation of the emission savings ratio when a non-renewable energy is used to power the BEV. As shown in *Figure 23*, the differences between the results obtained by using the regular Spanish energy mix and those obtained by testing fossil-fuel based electricity are striking: while a substitution is environmentally feasible after 8.88 years with the current electricity market, this period would increase to 28.80 years if the marginal mix were used. Therefore, there are no benefits related to this scenario when considering the vehicles' estimated lifetime.

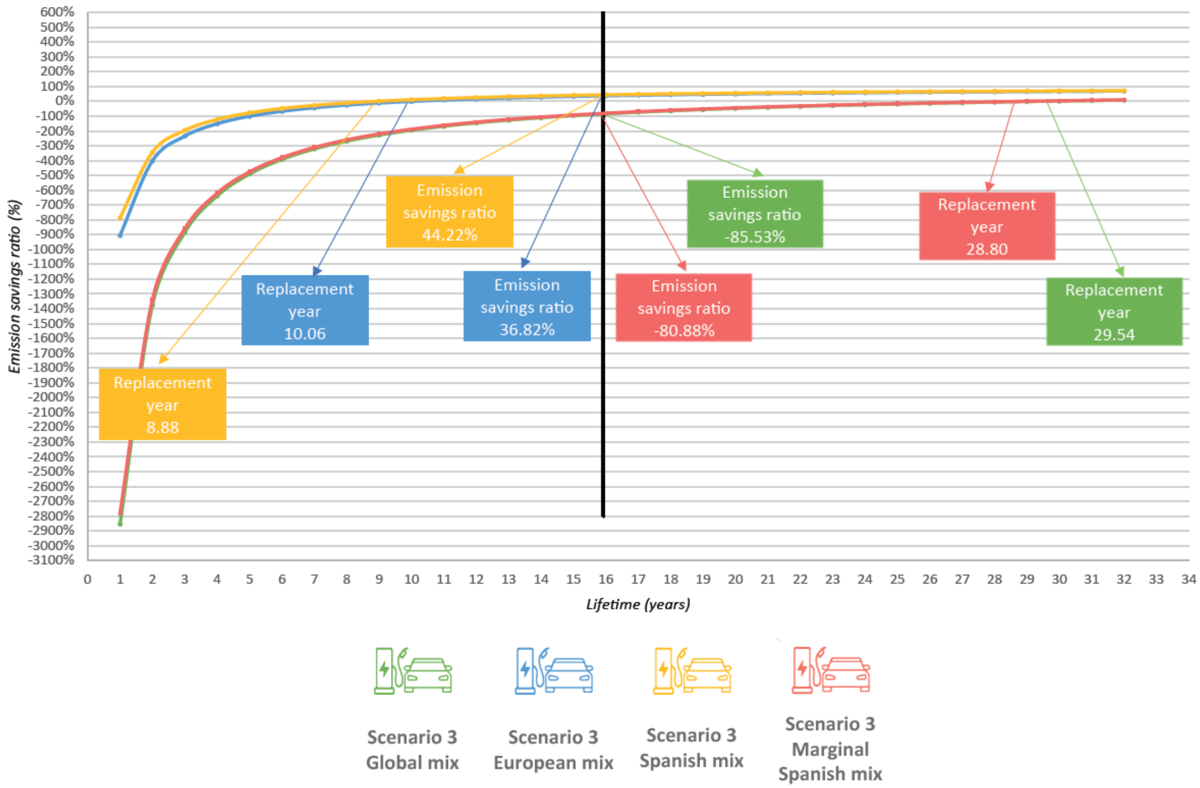

Figure 23. Emission savings ratio in the lifetime of the Scenario 3 with different regional energy mixes.

It has also been found that by the time the lifetime has ended, the emission savings ratio in Scenario 3 would be -85.53 % if the global energy mix is used to power the electric vehicle. Thus, this scenario would not be an environmentally optimal alternative, given that the EC of the new car would be higher than the savings associated with using it in place of the base vehicle. In addition, if the European energy mix were used, the emission savings ratio would increase to 36.82 % by the end of the lifetime, making it environmentally optimal to carry out the substitution after 10.06 years. Bearing this in mind, it is fair to state that measures aimed at promoting electrification, such as the scrappage schemes analysed by Kagawa et al. (2013) and Jiménez et al. (2016), would only be worthwhile if a renewable energy mix were ensured and if the average occupancy of the new electric vehicles could be increased to 3 passengers, as in Scenario 5, shown in *Table 16*.

The Spanish mix is the most sustainable of the electricity markets compared. Nonetheless, it is not feasible to choose in which region an electric car will be powered in real life. In this respect, policy makers could address the need for enhancing renewable energy availability when designing measures to boost BEV uptake, prioritising the sustainability of the electricity offered in a certain region over financial incentives that are not necessarily effective in encouraging BEV purchase, as demonstrated in the cases of the UK, China, the United States and France, where higher tax exemptions have been applied without achieving the same success as by some other countries, such as Norway and the Netherlands (Broadbent et al., 2018).

8.9 Conclusions

In this study, it has been demonstrated that up to 10.01 % of a petrol car's life-cycle carbon emissions could be saved if a EURO 5 compliant vehicle is used instead of a EURO 3 one. By switching from fuel to diesel, it is possible to reduce GWP by up to 20.50 % when comparing the base vehicle with a EURO 5 diesel car. However, when fine particulate matter formation is taken into account, the diesel car is 16.67 % more polluting than the base vehicle. Similarly, the electric car could mean an emission saving of up to 78.86 % in terms of GWP, but could be up to 61.13 % more polluting than the EURO 3 petrol car if fine particle matter emissions are taken into account.

By using the upgraded equations to compare the benefits of using the addressed vehicles, the optimal replacement year for a EURO 3 petrol car was estimated, taking into account the emission savings of continuing to use the old vehicle versus the impact reduction associated with the usage of the new car. From an environmental perspective, it can be concluded that the base vehicle can be replaced by a small-sized electric car after 8.88 years, which is 44.22 % of the average lifetime (estimated at 15.92 years), as long as the Spanish energy mix is used to power it. The substitution can be performed by 58.84 % of the average lifetime if the BEV is run with a 100 % renewable energy mix. Also, a small-sized electric car can be selected as the substitution option by 79.33 % of the estimated lifetime, if it is run with an average occupancy of 3 passengers and a 100 % renewable energy mix.

This research shows that if the EURO 3 petrol car has to be replaced by a EURO 5 petrol car, it is only suitable if this occurs at 27.93 years, which is 71.45 % higher than the estimated lifetime. From a perspective based exclusively on GWP, a EURO 5 diesel car is a better alternative to make the substitution, taking into account that it can save carbon emissions when used as a replacement car after 13.65 years, with an emission savings ratio of 14.25 % at the end of the operating period.

On the other hand, diesel cars have a considerable handicap in that their usage is related to higher impacts in other environmental categories when compared to petrol cars, as has been highlighted. In terms of life-cycle particulate matter emissions, there are no savings related to the diesel analysed. Therefore, it is not environmentally optimal to choose it as a substitution, if the air quality is selected as the main criteria. As this approach is focused only on GWP and fine particulate matter formation, future research could assess their optimal substitution time, looking at impacts such as human carcinogenic toxicity, human non-carcinogenic toxicity and terrestrial, freshwater and marine ecotoxicity.

The present study is limited by the possible effect of technological improvements and industrial advances on cleaner and sustainable production in the vehicle market. The replacement year yielded by each simulated scenario has a significant reliance on the reduction of GWP, achievable through the potential enhancement of the environmental efficiency in the production of new vehicles. Future research could tackle the real influence of developing vehicular eco-designed solutions on the applicability of decarbonisation strategies based on car replacement. Prospective LCA and patent analyses are also needed to measure the potential carbon footprint reductions associated with innovations in the vehicles' manufacturing processes.

However, this current approach can be considered for the assessment of the efficiency of scrappage schemes as a strategy to reduce carbon emissions from passenger transport. Our findings suggest that implementing a scrappage scheme aimed at boosting electric vehicles requires an accurate analysis of the energy mix in the market for electricity, given that BEVs would not be an optimal substitution option for an ICEV if the energy consumed to run the replacement car comes from fossil fuels and non-renewable sources, as demonstrated in section 3.3. Although, further research is needed to extend this approach to other mobility options including motorcycles and public vehicles.

It was also observed that the Spanish electricity market is more sustainable for powering an electric car than the global and European average markets, since the Spanish market has a 19.35 % renewable energy mix while the European and the global markets have a 17.46 % and 11.46 % renewable energy mix, respectively. It was estimated that if a BEV powered with the Spanish energy mix is chosen to replace a petrol car, the substitution could be 69.94 % faster than with an electric car using the global energy mix. It can be concluded that the cleaner the energy mix used to run the replacement car, the shorter the time to make an environmentally optimal substitution, so that scrappage schemes would only be worthwhile if a renewable energy mix is ensured.

9. Life Cycle Assessment via software tools: result analysis in a bicycle study

9. 4th article: Life Cycle Assessment via software tools: result analysis in a bicycle study

International conference article

32th INGEGRAF International Conference 21-23 June 2023, Cadiz.

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9.1. Conflicts of interest

The authors declare no competing financial interest.

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9.3 Abstract

There is a current need for enhancing the use of conventional bicycles in commuting since their life-cycle emissions are significantly lower than those of other means of transport. Despite several Life Cycle Assessments (LCA) have been performed to demonstrate the sustainability of bikes; the used method, the software employed, the datasets and the characterisation factors applied in the modelling process should be addressed in order to determine how these conditions can change the impact results of this vehicle. In this sense, the aim of this study was to quantify the life-cycle emissions from a conventional bike, performing LCA by means of two different technological approaches: the product system modeller of OpenLCA and the module for sustainable design of SolidWorks; in order to explore the specific parameters affecting the inventories, the results and the environmental loads of the processes related to the selected vehicle. Our analysis showed that the Global Warming Potential (GWP) obtained from SolidWorks is 12.69% higher than that from OpenLCA. This research concludes that the impacts related to the energy used in the extraction of raw materials, the types of supply acquired for production and the treatment of the used bicycle can influence the results of the Life Cycle Assessments performed.

Keywords: global warming; greenhouse gas emission; transportation system; carbon footprint; passenger travel.

9.4 Introduction

Enhancing the use of conventional bicycles for commuting is considered as a current need, since their life-cycle emissions are significantly lower than those of other means of transport: a study that aimed to assess the emission reduction of bike usage in sustainable cities showed that these vehicles release 6.08 g CO2-eq·pkm-1 while private cars and subways emit 187.48 and 31.83 g CO2-eq·pkm-1; which represents potential reductions ranging from 96.76 to 80.90% in Global Warming Potential (GWP) of transportation systems (Cheng Baoquan, 2022). As a sustainable means of transport, the bicycle is being widely used in sharing systems which are considered environmentally friendly for urban mobility. However, insufficiency in the final disposal processes may generate negative impacts that should be addressed by means of Life Cycle Assessment (LCA) (Mao et al., 2021).

In this context, the carbon emissions from the life-cycle of bikes have been quantified in several studies: Phillips (Philips et al., 2022) found that a conventional bicycle releases 16 g CO2-eq·pkm-1 if a lifespan of 15,000 km is considered, while the bike analysed by Montoya (Montoya-Torres et al., 2023) releases 15 g CO2-eq·pkm-1. Also, a study made by Spreafico (Spreafico & Russo, 2020) showed a GWP of 5 g CO2-eq·pkm-1 and other research made by Papon (Papon et al., 2019) yielded a per-kilometre life-cycle emission of 13.19 g CO2-eq. This is aligned with the findings from the studies carried out by Sun (Sun et al., 2023) and Migliore (Migliore et al., 2021), who exposed GWP of 15.6 and 10.5 g CO2-eq·pkm-1.

As we can see, the LCA results obtained from a literature review have an important drawback in that they tend to vary from one case study to another; hence it is pertinent to establish the parameters affecting the calculation of the GWP of products. In this sense, the LCA method, the software tool used for the analysis, the datasets and the characterisation factors applied in the modelling process should be addressed in order to determine how these conditions can change the outcomes from a modelled product system. For such purpose, a case study was designed in Brazil, by modelling a particleboard production process and using different software tools such as

SimaPro, openLCA, GaBi and Umberto. The analysis was carried out by means of the ILCD midpoint method and the obtained results were expressed in terms of maximum/minimum relative deviation. In summary, the ratio between the highest and the lowest result obtained for the climate change impact category was 1.02, which suggest an important similarity in the outcomes of the different software used. By contrast, the photochemical ozone formation category yielded the most dispersed results of the study, reaching a maximum/minimum relative deviation of 1.42 (Lopes Silva et al., 2019).

A similar study was carried out for the global processes of exploration and production of oil and gas, using SimpaPro and OpenLCA with the CML Baseline 2008 method and applying characterisation factors at Midpoint. As a result, the global warming impact value obtained from SimaPro was almost 60% higher compared to that from OpenLCA (Iswara et al., 2020). In this framework, Ren (Ren & Su, 2014) highlighted the use of SolidWorks as a 3D modeling CAD tool which can assess the sustainability of modeled parts or assemblies, but with a few important handicaps: carbon footprints may be not detailed enough for application in further design optimization (1) and the product can only be modeled via CAD, which is time consuming and complex work requiring professional knowledge (2).

As evidenced, several product system modellers have been addressed when comparing different LCA approaches and the deviations related to the used methodology and the selected software tool. Nonetheless, there are no comparisons found with results from CAD/CAM modellers to address the relation between product design and the use of LCA in industry. Therefore, the aim of this study was to quantify the GWP and the Total Energy Content of a conventional bike, performing Life Cycle Assessments by means of two different technological approaches: the product system modeller of OpenLCA and the module for sustainable design of SolidWorks; in order to explore the specific parameters affecting the inventories, the results and the environmental loads of the processes related to the life cycle of conventional bicycles. Also, this article aims to verify the CAD/CAM software tools as a primary strategy to insert the LCA and eco-design in the industrial processes, having the ability to create in real-time simulations of environmental impacts of new objects.

9.5 Methodology

For this research, the Ecoinvent 3.9 database was used in the modelling process performed via OpenLCA. Also, ReCiPe 2016 v.1.01 was the selected method for calculations, using a Hierarchist (H) perspective and applying characterisation factors at Midpoint. Meanwhile, the analysis performed by means of the module for sustainable design of SolidWorks was based on the GaBi environmental LCA database, using the CML method.

The *Figure 24* is a render design by Deschamps (2014). It shows a 17.23 kg bike that was selected for the LCA performed in the SolidWorks Sustainability module. Stages such as acquisition of raw materials, production, and final disposal were included in calculations, as well as the transport from the production point to the use place, assuming a 203 km land freight in South America for such purpose.

Figure 24. Design of the selected bicycle modelled in SolidWorks.

The inputs for the processes of raw materials acquisition and production were included in the life-cycle inventories, on the basis of the material intensity related to the bike shown in *Figure 24*; so that the amounts of metals and plastics were equally entered in both software tools. In the end-of-life of a used bicycle, the metals are fully recycled while the plastic parts are incinerated, according to Ecoinvent 3.9. However, this database does not specify the percentages of material sent to each final disposal process hence we estimated them by considering the share of metals and plastics in the total of inputs entered in the phase of raw materials acquisition; with the aim of using the same proportions in the end-of-life processes modelled in SolidWorks. In summary, *Table 17* gathers the main characteristics of the vehicles modelled in the selected software tools.

Table 17. Characteristics and description of the modelled bicycles.

Characteristic	Description
Weight	17.23 kg
Main material	Aluminum

Plastics used in manufacture	Rubber and nylon 6/10 in SolidWorks. Synthetic rubber and nylon 6 in Ecoinvent
Final disposal process	In Ecoinvent metals are fully recycled and plastics are incinerated. The respective percentages were estimated to be 93.08% and 6.92%, which were used in SolidWorks.

9.6 Results and discussion

The Life-Cycle Assessment perform in our research allowed us to make a comparison of GWP related to the selected bikes. The results from SolidWorks show that 202.2 kg CO_2-eq are emitted from the analysed vehicle when considering all the life cycle environmental impacts. As *Figure 25* shows, 94.91% of impacts corresponds to the stage of acquisition of raw materials, while energy and supplies for production account for 3.50% of contributions to the GWP of the analysed bicycle. Meanwhile, the assessment performed by means of OpenLCA yields a 93.82% contribution from materials and a 4.42% from production, to the life cycle carbon emissions of the 17,23 kg bicycle addressed in the Ecoinvent 3.9 database.

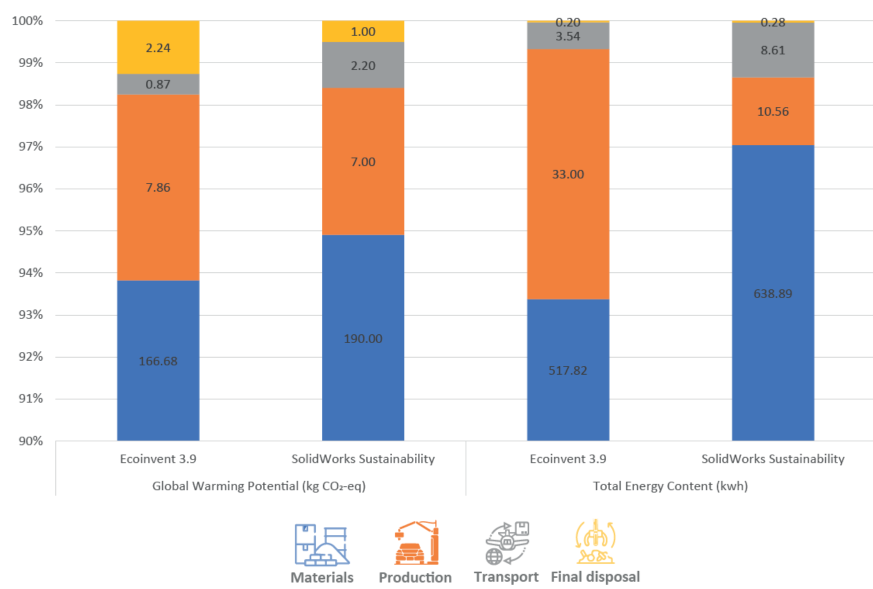

Figure 25. Contributions to GWP and Total Energy Content in OpenLCA and SolidWorks.

As it can be seen in *Table 18*, the Global Warming Potential obtained from the module for sustainable design of SolidWorks is 12.69% higher than that from Ecoinvent, while the Total Energy Content yielded by the former is 18.71% higher than that from Ecoinvent.

Table 18. Comparison of results of Global Warming Potential and Total Energy Content.

Phase	Global Warming Potential (kg CO_2-eq)			Total Energy Content (kwh)		
	Ecoinvent 3.9	SolidWorks Sustainability	% Increase over Ecoinvent	Ecoinvent 3.9	SolidWorks Sustainability	% Increase over Ecoinvent
Materials	166.68	190.00	13.99%	517.82	638.89	23.38%
Production	7.86	7.00	-10.94%	33.00	10.56	-68.01%
Transport	0.87	2.20	153.72%	3.54	8.61	143.37%
Final disposal	2.24	1.00	-55.45%	0.20	0.28	37.66%
Total	177.65	200.20	12.69%	554.56	658.33	18.71%

The contributions shown in Figure 25 are similar to those obtained by Papon (Papon et al., 2019) in a bicycle’s case study which exposed that the main contributor to climate change is the material preparation phase (74.4%) followed by the usage (15.5%) and the manufacturing phase (4.96%). In that research, it was also evidenced that the aluminum used in the frame production is mainly responsible (67.3%) for material consumption. In addition, the steel used in some other bicycle parts and the natural rubber used in the tire production also have significant impacts in the global warming category.

Regarding the evident difference in the GWP yielded by the compared software tools, it is fair to state that the database used in the module of sustainable design of SolidWorks may allocate higher environmental loads to the energy and supplies for the extraction of raw materials, since the main difference in the results yielded by both software tools corresponds to that phase. This can be due to the impacts related to the material providers: while Ecoinvent 3.9 have multiple options for selecting the provider process of each material, depending on the average impacts of the market in question; SolidWorks only allows entering the continents of manufacture and use.

Similarly, the impacts of the transport phase may be overestimated in the Life-Cycle Assessment carried out by SolidWorks, since this software does not allow establishing the vehicle type for the land freight, in the modelling process. Instead, it is possible to enter the distance and the region of assembly and use, while Ecoinvent offers multiple options of transport and allows to enter the corresponding amounts in terms of tkm (ton-kilometre), a more suitable unit for transport of goods.

Despite the bicycle's use phase was not considered in our modelling processes, it is noteworthy to mention that the assumed lifetime performance can be another factor with a significant influence on the final results. In the case of using Ecoinvent 3.9, the global warming impact values can be related to a functional unit such as g CO_2-eq$\cdot$pkm^{-1} (grams of carbon dioxide per passenger-kilometre) that has an important reliance on the total mileage assumed for a usage phase. Meanwhile, SolidWorks calculates only a totalized GWP with no specific mileage.

In this sense, diverse mileages can be feasibly used, depending on the conditions aimed to be exposed in a study. For instance, the average daily ridership values for The Netherlands were found to vary between 1.4 and 6.2 km per day. In this case, if a 6.2 km$\cdot$day^{-1} travelled distance is assumed, a total of 1,387 km per year can be considered in the calculation of a bicycle's lifetime performance (Bonilla-Alicea et al., 2020); resulting in a total mileage of 20,805 km if a 15-year lifespan is taken into account. This contrasts with the lifespan of 46,411.07 km addressed by Wang (Wang et al., 2021).

Another factor that may affect the LCA results can be the energy expenditure in the use phase. In this respect, Severis (Severis et al., 2022) states that some mobility lifestyles are more sensitive to human energy expenditure, especially when the modes of transport present low input and output inventory parameters, as in the case of walking or cycling. His study concludes that the inclusion of energy expenditure in the LCA of the passenger transport on foot, by bicycle, automobile, bus and airplane; increased the impacts in the range of 4–33% in the climate change category. In this sense, our approach did not consider the energy expenditure in any of the LCA performed. Nonetheless, it could be observed that this condition can only be addressed when using OpenLCA, by means of the Exiobase datasets: in the analysis carried out by Montoya (Montoya-Torres et al., 2023), a per calory food price was considered in order to estimate the impacts of energy consumption related to cycling.

9.7 Conclusions

This research concludes that the impacts related to the energy used in the extraction of raw materials, the types of supply acquired for production and the treatment of the used bicycle can influence the results of the Life Cycle Assessments performed. Furthermore, the end-of-life process included in Ecoinvent 3.9 assumes that aluminium and steel parts are fully recycled, and only plastics are incinerated without mentioning the percentages of materials sent to each final disposal process. Despite the fact that we estimated these percentages in order to apply them in the modellin process carried out by means of SolidWorks, this software tool yielded a 55.45% lower impact in that phase.

Finally, it can be suggested using OpenLCA when modelling a complex product system, taking into account that processes included in Ecoinvent 3.9 can be copied, moved and modified if necessary. This can be useful in an LCA, especially if we have to add specific parameters in unit processes or modify reference flows affecting the product system. Nevertheless, the sustainability module of SolidWorks can be a better option when a new product is being designed and there is a need for testing the viability of a specific material related to a certain mass contribution within the addressed product.

10. Key learnings and discussion

10. Key learnings and discussion

Within the learnings of the present research, we can find that the number of trips made by the passengers and the distances travelled by the vehicles have a significant influence on a city's carbon emissions, so that urban areas have an important drawback when integrating sustainable means of transport. In this sense, restricting commuting could be the most effective measure to reduce the life-cycle emissions from private and public vehicles, while electrification can be a strategy for decarbonising cities as long as the environmental feasibility of vehicle replacement is taken into account. Table 19 gathers the main results of the three main contributions and the conference article that comprises the present Doctoral Thesis.

Table 19. Main results obtained from the four contributions of the thesis.

Specific objective 1: To comprehensively clarify the differences between urban and rural settings when estimating and comparing life-cycle carbon emissions from private transportation systems.	
No.	**Outcome description**
1	Considering the fleet split of the settings analysed, the weighted average emissions from vehicles in the rural area are lower than those in the urban area. This is mostly due to the average occupancy and its influence on the GWP of a city's vehicles. Thus, the ratio of passengers per vehicle is currently higher in the rural area compared to the urban setting.
2	Among two-wheel vehicles, the LCA comparison shows a significant potential reduction associated with electric motorcycles when comparing with conventional motorcycles, in terms of CO_2-eq savings for both of the areas analysed.
3	Regarding four-wheel vehicles, the CO_2-eq emissions of electric cars are significantly lower than those of diesel and petrol cars. Nonetheless, the good environmental performance of BEVs may be due to the highly renewable energy comprised in the electricity market of both areas, which corresponds mostly to hydro energy.
4	Despite a conventional scooter having a lower material consumption in its production and occupying less volume for distribution operations than a four-wheel vehicle, this means of transport emits more life-cycle carbon dioxide than an electric car in the analysed urban setting.
5	It is fair to state that diesel is a better fossil-based alternative over gasoline, since it has been detected a reduction of life-cycle carbon emissions when comparing diesel and petrol cars in both areas analysed. However, it should be considered the impacts in air quality associated with the use of ICEVs and the combustion of fossil fuels in the transport sector.

No.	Outcome description
6	The main contribution to GWP corresponds to the use phase in petrol and diesel cars. This emphasises the influence of fossil-related tailpipe emissions on the life-cycle impacts of ICEVs since, in BEVs, the contribution of usage is significantly lower. Nonetheless, in electric cars the phase of raw materials acquisition accounts for a notable proportion of life-cycle emissions, which suggest that the improvement of efficiency in extraction and production processes should be considered in vehicular electrification.
7	The daily emissions of a vehicle have a strong dependence on the per-day trips made by its passengers. For instance, the daily carbon emissions from automobiles of the urban area are significantly higher than those from motorcycles. At the same time, the per-passenger daily emissions from bicycles are lower than those from scooters. This has an explanation in that conventional scooters and petrol cars alone are responsible for most of the trips made by individual and private transportation systems in the urban area.
8	In the rural area, despite the fact that conventional scooters have lower per-passenger-kilometre emissions than diesel cars, their travelled distances and number of daily trips are considerably higher, resulting in more CO_2-eq·p^{-1}·day^{-1} emissions.
9	There is a clear difference between the daily CO_2-eq per passenger emitted by vehicles in the urban area and those of transportation systems in the rural area: based on weighted averages, it can be stated that the urban transportation systems emit more daily than those of the rural area. This is due to an extensive usage of traditional vehicles, with a low average occupancy and a high number of daily trips in the analysed urban setting.

Specific Objective 2: To simulate eight scenarios to reduce the annual carbon emissions from passenger transport in a city, taking into account the GWP of public and private vehicles, obtained by means of LCA.

No.	Outcome description
1	The individual environmental performance of vehicles contrasts with that of fleet emissions. For instance, a regular bus emits less carbon dioxide than petrol and diesel cars in terms of passenger-kilometre, but the local fleet of buses has the second highest emissions per day of the analysed city. This is due to the high mobility of these vehicles, as they cover long distances with a high number.
2	Up to a quarter of the carbon emissions from passenger transport could be saved, by augmenting the occupancy ratio of private and public vehicles of a medium-sized city or increasing the modal shares of means of transport such as diesel cars, bicycles, BEVs and BEVs run with renewable energy.
3	Augmenting the fleet of diesel cars can yield a higher reduction of cumulative energy demand when compared with other measures such as increasing the bicycle modal share, especially when using a regular energy mix for running electric bikes. This may diminish the environmental benefits of cycling in terms of total energy content, hence 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.
4	If the particulate matter impact category is selected as the main criterion for the analysis, increasing the use of diesel cars would be counterproductive and the total emissions of the analysed city would be actually increased.
5	Increasing the fleet of public buses as well as their average occupancy has proved to be the second most effective measure to reduce the total annual carbon emissions of the analysed city. About half of the life-cycle emissions from public and private vehicles could be saved by enhancing the use of regular buses.

No.	Outcome description
6	Restricting a city's mobility could be the most effective strategy for reducing GHG levels in a medium-sized city. This requires to decrease the average number of individual trips per day in private and public vehicles, as well as reducing the average distance travelled of private means of transport. In this sense, promoting homeworking could be key in discouraging commuting.

Specific objective 3: To establish the environmentally optimal time within which to replace a petrol car, using a life-cycle perspective to analyse the impacts of the substitution options.

No.	Outcome description
1	The most sustainable replacement alternative for a EURO 3 petrol car is an electric car powered with 100 % renewable energy and run with an average occupancy of 3 passengers. In this case, the substitution can be performed sooner than when using other types of vehicles such as EURO 5 diesel and petrol cars or a BEV run with a regular energy mix.
2	The use phase has the highest contribution to GWP in ICEVs while the production phase is responsible for the most of the carbon emissions in the case of BEVs. This underlines the impact of fossil fuel combustion in the life-cycle emissions of conventional cars and also that BEV manufacturing efficiency should be prioritised for the purpose of implementing vehicular electrification to mitigate climate change.
3	It is not environmentally optimal to replace a EURO 3 petrol car with the EURO 5 version of the same vehicle over the course of its lifespan, since the emissions savings associated with performing the substitution are lower than the impacts of continuing to use the former.
4	A EURO 5 diesel car can also be a substitution option for the base vehicle and could be recommended instead of the EURO 5 petrol car, since the optimal replacement time in this case is 1.75 times the estimated lifetime. Nevertheless, if the particulate matter impact category is selected as the main criterion for the analysis, diesel and electric vehicles would no longer be a substitution option for a EURO 3 petrol car, as there would be no environmental savings associated with these vehicles.
5	Technological improvements that imply a reduction in the GWP of the substitution vehicles could reduce the time within which to replace the old car. Indeed, the ICEVs are the most sensitive to these kinds of improvements when considered as substitutes for a EURO 3 petrol car.
6	The environmental performance of a BEV depends significantly on the energy mix used to power it. Thus, measures aimed at promoting electrification, such as scrappage schemes would only be worthwhile if a renewable energy mix were ensured.

Methodological objective 1: To compare the outcomes of LCA performed on a passenger vehicle using two different technological approaches: OpenLCA and SolidWorks.

No.	Outcome description
1	The contributions to the Global Warming Potential of the analysed vehicle, as yielded by the product system modeller of OpenLCA and the module for sustainable design of SolidWorks, are similar in terms of kg CO_2-eq. emitted in the phases of raw materials extraction and production.
2	The results of the Life Cycle Impact Assessment obtained from SolidWorks are higher than those from OpenLCA. This can be seen when analysing the life-cycle emissions in two impact categories: Global Warming Potential and Total Energy Content.

3	In the case of bicycles, the material used in the production of the frame is the main cause of material consumption and the major contributor to the vehicle's Global Warming Potential. Thus, the acquisition of raw materials and the manufacturing processes associated with a vehicle used as active means of transport should be prioritised in the proposal of strategies for cleaner and sustainable production.
4	The database of the module of sustainable design of SolidWorks may allocate higher environmental loads to the energy and the supplies for the extraction of raw materials, when compared to the Ecoinvent database. The main difference in the results yielded by both software tools corresponds to the phase of acquisition of raw materials.
5	The impacts associated with the transport phase may be overestimated in the LCA performed by means of SolidWorks, given that the vehicle type for the land freight cannot be established in the modelling process of this software. It is possible only to enter the distance of distribution and the regions of assembly and use, while Ecoinvent offers a wide range of options to set the transport process and allows to enter the corresponding amounts in terms of tkm (ton-kilometre), which is a more suitable unit for transport of goods.
6	The bicycle's lifetime performance could be another factor with a significant influence on the GWP results. When using Ecoinvent 3.9, the outcomes can be related to a functional unit such as g CO_2-eq·pkm^{-1}. This unit has an important reliance on the total mileage assumed for a usage phase. Instead, SolidWorks calculates only the total GWP with no specific mileage.

Sustainable transport has been found to be key in achieving the sustainable development goals. Not only because it facilitates the mobility of people and goods for meeting basic necessities, but also because of its ability of accelerating the achievement of crucial goals such as combatting climate change and reducing inequality (Department of Economic and Social Affairs, 2021). In this sense, a sustainable transport system should be reliable, efficient, safety and have minimal environmental impact on public health, environment, economy and urban planning (Gołda et al., 2017).

The environmental issues associated with the transport sector are frequently discussed from four perspectives: models and indicators to assess sustainability and performance of vehicles, GHG emissions and environmental impacts, alternative fuels and transport policy (Zhao et al., 2020). The present thesis addresses the carbon footprints of vehicles and the feasibility of policy measures aimed at reducing passenger transport emissions, from a life-cycle perspective. As can be seen in the first two scientific contributions presented, applying LCA in the analysis of a vehicle's performance provides a complete view of the effects of potential improvements that can be made in the production and usage of public and private means of transport.

Also, the considerations on vehicle electrification and scrappage schemes discussed in the third article offer alternative criteria to assess the effectiveness of low-carbon transport, as it has been widely researched in scientific literature. In this regard, a hidden barrier to the electrification of transportation is a lack of recognition of what it implies: availability of home chargers for every BEV, a network of direct-current fast chargers and a highly renewable energy mix (Tamor & Stechel, 2022). The approach adopted in this research promotes the evaluation of a region's conditions in terms of infrastructure, social behaviour, commuting patterns and economic policy, for designing suitable strategies to reduce GHG emissions taking into account the life-cycle impacts of means of transport.

Against this backdrop, the learnings from this study allow to infer that the environmental benefits of sustainable mobility strategies should be assessed from a life-cycle perspective instead of taking into account only direct exhaust fumes or the operational impacts of vehicles. In addition, it has been detected that a wide range of impact categories should be considered when comparing measures for decarbonisation, instead of assessing only the carbon emissions of vehicles. As it could be observed when calculating the environmentally optimal time to replace old vehicles, the feasibility of car substitution-based strategies relies greatly on whether the particulate matter formation or the Global Warming Potential of vehicles is taken into account.

Adopting a circular economy model represents an opportunity to influence on key factors affecting the environmental performance of electric vehicles, such as vehicle design, use patterns, recycling processes and energy mix (European Environment Agency, 2018). Hence, integrating technological improvements in the production and end-of-life of vehicles, as well as promoting lifespan optimisation as suggested in the third contribution of this thesis, could be central to achieve a high level of circularity in passenger transport, as needed to experience less than 1.5°C of global warming by 2030 (World Economic Forum, 2021).

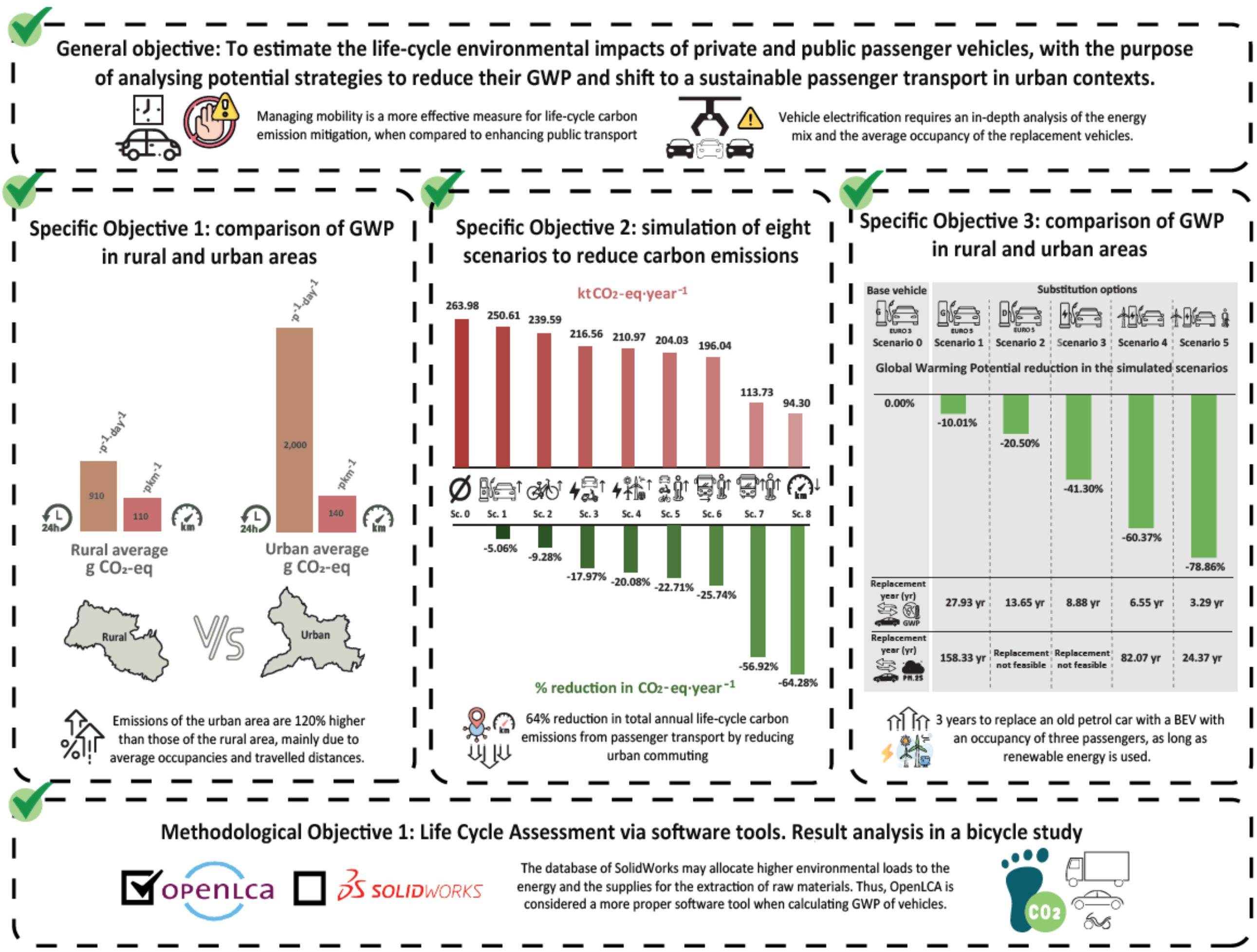

Figure 26. Summary of learnings and main outcomes.

11. Conclusions

11. Conclusions

The main goal of the current study was to determine the conditions required to shift to a sustainable passenger transport in the urban context. To that end, different case studies were conducted in order to compare the GHG emissions from private and public vehicles in multiple settings, including simulated scenarios designed to measure the effectiveness of strategies aimed at reducing environmental impacts associated with commuting.

It was hypothesised that enhancing the use of public transport and promoting vehicle electrification would be key in meeting sustainable transport in urban scenarios. Nonetheless, this research argues that managing mobility is a more effective measure for life-cycle carbon emission mitigation and that vehicle electrification requires an in-depth analysis of the energy mix and the average occupancy of the replacement vehicles. As can be seen in Section 3, this work established a set of specific hypotheses regarding the expected outcomes from each case study. In this sense, the conclusions drawn to response to each hypothesis are described as follows:

a) Specific conclusion 1: In the first contribution of this thesis, it was concluded that the life-cycle carbon emissions from private vehicles in the urban setting are significantly higher than those of the rural area, as it has been established in the Specific hypothesis 1. Overall, the occupancy ratio, the distances travelled and the frequency of trips made in private vehicles are influential conditions affecting the environmental performance of the vehicles in each area.

   These findings allowed to prioritise the analysis of mobility strategies focused on urban areas, as it was subsequently explored in this work. However, future projects could study the carbon footprints of carsharing services when integrated to public transport, in order to shed light on the environmental performance of these kinds of transportation systems in the urban and rural areas.

b) Specific conclusion 2: As can be seen in the second article, this work proposed scenarios to reduce the most polluting vehicles, enhance the modal shares of public and private means of transport, and boost the use of electric vehicles and bicycles; with the aim of providing valuable information to contribute to the quest for smart and sustainable cities and facilitate urban development and policy planning in future projects.

   In the analyses performed in this part of the research, it could be demonstrated that the most sustainable measures for life-cycle carbon emission mitigation are managing mobility and restricting commuting, as opposed to the Specific hypothesis 2 which stated that increasing the modal share of public transport would lead to the highest local emission reduction. However, the present study did not assess 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.

   Also, further studies could explore how public entities can boost the adoption of alternative technologies to complement mobility electrification, as well as tackle the social cost and economic impact associated to a reduction of commuting, given that this approach only took into account the environmental aspects of the measures tested.

c) Specific conclusion 3: As it has been hypothesised in Section 3 (Specific hypothesis 3), replacing an Internal Combustion Engine Vehicle (ICEV) with a Battery Electric Vehicle (BEV) is worthwhile only if the substitution option is run with a renewable energy mix. Nonetheless, the analyses conducted for the third article were limited by the possible effect of technological improvements and industrial advances on cleaner and sustainable production in the vehicle market.

The environmentally optimal time to replace a EURO 3 petrol car obtained in the simulations performed in this study had a significant reliance on the reduction of GWP, achievable through the potential enhancement of the environmental efficiency in the production of new vehicles. Thus, the real influence of enhancing eco-designed cars on the feasibility of car substitution-based strategies for decarbonisation, should be further studied. In this sense, prospective LCA and patent analyses are also needed to measure the potential carbon footprint reductions associated with innovations in the vehicles' manufacturing processes.

Finally, future research should assess the optimal substitution time for old vehicles, looking at impact categories such as human carcinogenic toxicity, human non-carcinogenic toxicity and terrestrial, freshwater and marine ecotoxicity, given that this approach was focused only on GHG emissions and Total Energy Content.

d) Methodological conclusion 1: The results of the fourth article allow to conclude that the database used in the module of sustainable design of SolidWorks allocates higher environmental loads to the energy and supplies used in the extraction of raw materials and the transport phase. It could be observed that the results of Global Warming Potential and Total Energy Content obtained from OpenLCA are more accurate than those from SolidWorks, as it has been hypothesised in Section 3 (Methodological hypothesis 1).

Respecting the implications of these conclusions for future research, it has been suggested using OpenLCA when modelling a complex product system that requires to include specific parameters in unit processes or modify reference flows affecting the product system. Meanwhile, the sustainability module of SolidWorks can be a better option when a new product is being designed and there is a need for testing the viability of a specific material related to a certain mass contribution within the addressed product.

12. References

12. References

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13. Supporting information

13. Supporting information

Supporting Information for:

Measuring life-cycle carbon emissions of private transportation in urban and rural settings

Table S1. Per-calorie food price estimation and Global Warming Potential of energy consumption for bike riding.

Food	**Colombian updated food price (DANE, 2023)** (€·kg^{-1})	**Energetic value (Instituto Colombiano de Bienestar Familiar, 2023)** (kcal·kg^{-1})	**Per-kilocalorie food price** (€·kcal^{-1})	**GWP of food** (kg CO2eq·€$^{-1}$)	**Energy consumption for riding** (kcal·km^{-1})		**GWP of consumption for riding (15,000 km)** (kg CO_2eq)
Meat	4.67	2770	1.68E-03	0.2397	Bike	31	112.85
Rice	0.75	1530	4.88E-04				
Beans	2.37	3360	7.05E-04				
Potato	0.39	810	4.80E-04				
Tomato	0.31	190	1.64E-03		e-bike	10.8	39.32
Onion	0.59	300	1.97E-03				
Average	1.51	1493.33	1.01E-03				

Table S2. Usage emissions from the analysed petrol car based on data from Asociación Colombiana de Vehículos Automotores (2017).

PETROL CAR		
Description	**Unit**	**Amount**
Emissions		
Ammonia	kg	15.36
Carbon dioxide	t	41.552
Carbon monoxide	t	4.304
Dinitrogen monoxide	kg	1.2
Methane	kg	3.12
Nitrogen oxides	kg	63.36
Particulates	kg	0.72
VOC, volatile organic compounds	kg	15.6

Table S3. Comparative of average contributions from the life-cycle stages of the analysed vehicles.

Analysed area	Vehicle	Acquisition	Production	Distribution	Usage	Maintenance	Final disposal
Ibagué: urban area	Petrol car	11.46%	0.87%	0.45%	83.91%	1.66%	1.65%
	Diesel car	10.92%	1.31%	0.66%	83.29%	1.58%	2.24%
	Electric car	39.42%	2.65%	1.61%	47.77%	3.02%	5.54%
	Conventional scooter	6.35%	0.15%	0.02%	87.88%	4.40%	1.20%
	Electric scooter	39.63%	0.46%	2.70%	21.38%	30.32%	5.52%
	Electric bike	37.36%	1.83%	4.41%	25.57%	27.73%	3.10%
	Conventional bike	33.56%	2.55%	0.83%	54.21%	8.35%	0.50%
	Weighted average	**10.66%**	**0.57%**	**0.30%**	**82.55%**	**4.61%**	**1.30%**
Venadillo: rural area	Petrol car	11.46%	0.87%	0.44%	83.91%	1.66%	1.66%
	Diesel car	10.92%	1.31%	0.65%	83.30%	1.58%	2.24%
	Electric car	39.43%	2.65%	1.57%	47.79%	3.02%	5.54%
	Conventional scooter	6.35%	0.15%	0.03%	87.87%	4.40%	1.20%
	Electric scooter	39.63%	0.46%	2.70%	21.38%	30.32%	5.52%
	Electric bike	37.37%	1.83%	4.39%	25.57%	27.73%	3.11%
	Conventional bike	33.57%	2.55%	0.79%	54.23%	8.36%	0.50%
	Weighted average	**11.89%**	**0.73%**	**0.27%**	**81.61%**	**4.27%**	**1.23%**
Difference from urban to rural case study		**-1.23%**	**-0.16%**	**+0.04%**	**+0.94%**	**+0.34%**	**+0.07%**

Table S4. Sensitivity analysis of electric cars GWP with increases in EV manufacturing efficiency.

Current EV manufacture efficiency				
Vehicle	**Venadillo**		**Ibagué**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**
Eléctric car	37,82	89,87	39,59	94,12
5% Increase in EV manufacture efficiency				
Vehicle	**Venadillo**		**Ibagué**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**
Eléctric car	35,93	87,98	37,61	92,14
10% Increase in EV manufacture efficiency				

Vehicle	Venadillo		Ibagué	
	Manufacture gCO_2-eq·pkm^{-1}	Total gCO_2-eq·pkm^{-1}	Manufacture gCO_2-eq·pkm^{-1}	Total gCO_2-eq·pkm^{-1}
Eléctric car	34,04	86,09	35,63	90,16
15% Increase in EV manufacture efficiency				
Vehicle	**Venadillo**		**Ibagué**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**
Eléctric car	32,15	84,20	33,65	88,18
20% Increase in EV manufacture efficiency				
Vehicle	**Venadillo**		**Ibagué**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**
Eléctric car	30,25	82,31	31,67	86,20
25% Increase in EV manufacture efficiency				
Vehicle	**Venadillo**		**Ibagué**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**
Eléctric car	28,36	80,42	29,69	84,22
30% Increase in EV manufacture efficiency				
Vehicle	**Venadillo**		**Ibagué**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**
Eléctric car	26,47	78,53	27,71	82,24

Table S5. Sensitivity analysis of average GWP with increases in the fleet of electric vehicles.

Current EV fleet share								
Vehicle	**Venadillo**		**Ibagué**		**Fleet Vehicles**		**Fleet share %**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**	**Ibagué**	**Venadillo**	**Ibagué**	**Venadillo**
Petrol car	2.30	264.64	2.41	277.02	49534.00	2410.00	25.24%	23.12%
Diesel car	3.08	235.35	3.23	246.38	392.00	398.00	0.20%	3.82%
Eléctric car	2.38	89.87	2.49	94.12	20.00	0.00	0.01%	0.00%
Conventional scooter	0.10	66.28	0.15	100.01	125314.00	6012.00	63.86%	57.68%

Electric scooter	0.01	21.62	0.02	32.63	16.00	0.00	0.01%	0.00%
Electric bike	0.38	20.90	0.38	20.90	4888.00	0.00	2.49%	0.00%
Conventional bike	0.38	15.02	0.38	15.03	16083.00	1603.00	8.20%	15.38%
Average		110.71		136.04				
2% Increase in EV fleet share								
Vehicle	**Venadillo**		**Ibagué**		**Fleet Vehicles**		**Fleet share %**	
	Manufacture gCO$_2$-eq·pkm^{-1}	**Total gCO$_2$-eq·pkm^{-1}**	**Manufacture gCO$_2$-eq·pkm^{-1}**	**Total gCO$_2$-eq·pkm^{-1}**	**Ibagué**	**Venadillo**	**Ibagué**	**Venadillo**
Petrol car	2.30	264.64	2.41	277.02	45609.06	2201.54	23.24%	21.12%
Diesel car	3.08	235.35	3.23	246.38	392.00	398.00	0.20%	3.82%
Eléctric car	2.33	89.83	2.44	94.07	3944.94	208.46	2.01%	2.00%
Conventional scooter	0.10	66.28	0.15	100.01	121389.06	5803.54	61.86%	55.68%
Electric scooter	0.01	21.62	0.02	32.63	3940.94	208.46	2.01%	2.00%
Electric bike	0.37	20.89	0.37	20.90	4888.00	0.00	2.49%	0.00%
Conventional bike	0.38	15.02	0.38	15.03	16083.00	1603.00	8.20%	15.38%
Average		106.33		131.03				
4% Increase in EV fleet share								
Vehicle	**Venadillo**		**Ibagué**		**Fleet Vehicles**		**Fleet share %**	
	Manufacture gCO$_2$-eq·pkm^{-1}	**Total gCO$_2$-eq·pkm^{-1}**	**Manufacture gCO$_2$-eq·pkm^{-1}**	**Total gCO$_2$-eq·pkm^{-1}**	**Ibagué**	**Venadillo**	**Ibagué**	**Venadillo**
Petrol car	2.30	264.64	2.41	277.02	41684.12	1993.08	21.24%	19.12%
Diesel car	3.08	235.35	3.23	246.38	392.00	398.00	0.20%	3.82%
Eléctric car	2.29	89.78	2.39	94.02	7869.88	416.92	4.01%	4.00%
Conventional scooter	0.10	66.28	0.15	100.01	117464.12	5595.08	59.86%	53.68%
Electric scooter	0.01	21.62	0.02	32.63	7865.88	416.92	4.01%	4.00%
Electric bike	0.37	20.88	0.37	20.89	4888.00	0.00	2.49%	0.00%
Conventional bike	0.38	15.02	0.38	15.03	16083.00	1603.00	8.20%	15.38%
Average		101.93		126.02				
6% Increase in EV fleet share								
Vehicle	**Venadillo**		**Ibagué**		**Fleet Vehicles**		**Fleet share %**	
	Manufacture gCO$_2$-eq·pkm^{-1}	**Total gCO$_2$-eq·pkm^{-1}**	**Manufacture gCO$_2$-eq·pkm^{-1}**	**Total gCO$_2$-eq·pkm^{-1}**	**Ibagué**	**Venadillo**	**Ibagué**	**Venadillo**
Petrol car	2.30	264.64	2.41	277.02	37759.18	1784.62	19.24%	17.12%
Diesel car	3.08	235.35	3.23	246.38	392.00	398.00	0.20%	3.82%

Eléctric car	2.24	89.73	2.34	93.97	11794.82	625.38	6.01%	6.00%
Conventional scooter	0.10	66.28	0.15	100.01	113539.18	5386.62	57.86%	51.68%
Electric scooter	0.01	21.62	0.02	32.63	11790.82	625.38	6.01%	6.00%
Electric bike	0.36	20.88	0.36	20.88	4888.00	0.00	2.49%	0.00%
Conventional bike	0.38	15.02	0.38	15.03	16083.00	1603.00	8.20%	15.38%
Average		97.54		121.01				
8% Increase in EV fleet share								
Vehicle	**Venadillo**		**Ibagué**		**Fleet Vehicles**		**Fleet share %**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**	**Ibagué**	**Venadillo**	**Ibagué**	**Venadillo**
Petrol car	2.30	264.64	2.41	277.02	33834.24	1576.16	17.24%	15.12%
Diesel car	3.08	235.35	3.23	246.38	392.00	398.00	0.20%	3.82%
Eléctric car	2.19	89.68	2.29	93.92	15719.76	833.84	8.01%	8.00%
Conventional scooter	0.10	66.28	0.15	100.01	109614.24	5178.16	55.86%	49.68%
Electric scooter	0.01	21.62	0.02	32.63	15715.76	833.84	8.01%	8.00%
Electric bike	0.35	20.87	0.35	20.87	4888.00	0.00	2.49%	0.00%
Conventional bike	0.38	15.02	0.38	15.03	16083.00	1603.00	8.20%	15.38%
Average		93.15		116.00				
10% Increase in EV fleet share								
Vehicle	**Venadillo**		**Ibagué**		**Fleet Vehicles**		**Fleet share %**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**	**Ibagué**	**Venadillo**	**Ibagué**	**Venadillo**
Petrol car	2.30	264.64	2.41	277.02	29909.30	1367.70	15.24%	13.12%
Diesel car	3.08	235.35	3.23	246.38	392.00	398.00	0.20%	3.82%
Eléctric car	2.14	89.64	2.24	93.87	19644.70	1042.30	10.01%	10.00%
Conventional scooter	0.10	66.28	0.15	100.01	105689.30	4969.70	53.86%	47.68%
Electric scooter	0.01	21.62	0.02	32.63	19640.70	1042.30	10.01%	10.00%
Electric bike	0.34	20.86	0.34	20.87	4888.00	0.00	2.49%	0.00%
Conventional bike	0.38	15.02	0.38	15.03	16083.00	1603.00	8.20%	15.38%
Average		88.75		110.99				
12% Increase in EV fleet share								
Vehicle	**Venadillo**		**Ibagué**		**Fleet Vehicles**		**Fleet share %**	
	Manufacture gCO_2-eq·pkm^{-1}	**Total gCO_2-eq·pkm^{-1}**	**Manufacture gCO_2-eq·pkm^{-1}**	**Total gCO_2-eq·pkm^{-1}**	**Ibagué**	**Venadillo**	**Ibagué**	**Venadillo**

Petrol car	2.30	264.64	2.41	277.02	25984.36	1159.24	13.24%	11.12%
Diesel car	3.08	235.35	3.23	246.38	392.00	398.00	0.20%	3.82%
Eléctric car	2.10	89.59	2.19	93.82	23569.64	1250.76	12.01%	12.00%
Conventional scooter	0.10	66.28	0.15	100.01	101764.36	4761.24	51.86%	45.68%
Electric scooter	0.01	21.62	0.02	32.63	23565.64	1250.76	12.01%	12.00%
Electric bike	0.34	20.85	0.34	20.86	4888.00	0.00	2.49%	0.00%
Conventional bike	0.38	15.02	0.38	15.03	16083.00	1603.00	8.20%	15.38%
Average		84.35		105.97				

Supporting Information for:

Towards sustainable passenger transport: carbon emission optimisation scenarios for a mid-sized city

Table S1. Inventory data for Life-Cycle Assessment of the analysed bus

Description	**Unit**	**Amount**
ACQUISITION OF RAW MATERIALS AND PRODUCTION		
INPUTS		
acetic acid, without water, in 98% solution state	kg	0.066
alkyd paint, white, without solvent, in 60% solution state	kg	30
aluminium, cast alloy	kg	1670
brass	kg	3
cast iron	kg	1030
copper, cathode	kg	109
diesel	kg	7.154793596
diesel	kg	14.44000968
diesel	kg	1.011463613
diesel	kg	1.461951323
diesel	kg	0.343960488
diesel	kg	142.5878213
diesel, burned in building machine	MJ	20.1
electricity, medium voltage	kWh	11.45720917

electricity, medium voltage	kWh	2797.452867
electricity, medium voltage	kWh	1284.696276
electricity, medium voltage	kWh	59.74859469
electricity, medium voltage	kWh	394.3023307
electricity, medium voltage	kWh	192.3427221
flat glass, coated	kg	490
heat, district or industrial, natural gas	MJ	31809.74486
heat, district or industrial, natural gas	MJ	490.2551438
heat, district or industrial, other than natural gas	MJ	860.3511195
heat, district or industrial, other than natural gas	MJ	0.348880484
hydrochloric acid, without water, in 30% solution state	kg	0.189
lead	kg	90
lime, hydrated, packed	kg	0.31
lubricating oil	kg	80.1
nitric acid, without water, in 50% solution state	kg	0.014974793
nitric acid, without water, in 50% solution state	kg	0.0351569
nitric acid, without water, in 50% solution state	kg	0.005517339
nitric acid, without water, in 50% solution state	kg	0.004613247
nitric acid, without water, in 50% solution state	kg	0.011514912
nitric acid, without water, in 50% solution state	kg	0.018976091
nitric acid, without water, in 50% solution state	kg	0.004630385
nitric acid, without water, in 50% solution state	kg	0.003116333
pig iron	kg	502
pitch	kg	42.56561203
pitch	kg	0.481824332
pitch	kg	7.529603175
pitch	kg	2.919088534
pitch	kg	0.166364069
pitch	kg	0.337507858
polyethylene, high density, granulate	kg	553
propylene glycol, liquid	kg	26
refrigerant R134a	kg	2
reinforcing steel	kg	4540
road vehicle factory	Item(s)	8.73E-07
section bar rolling, steel	kg	502

sheet rolling, steel	kg	568
sodium hydroxide, without water, in 50% solution state	kg	0.381
steel, chromium steel 18/8, hot rolled	kg	690
steel, low-alloyed, hot rolled	kg	22.8
stone wool, packed	kg	396
sulfuric acid	kg	34
synthetic rubber	kg	405
tap water	kg	33.31442473
tap water	kg	255.2827273
tap water	kg	1280.597606
tap water	kg	14654.52872
tap water	kg	94.76231587
tap water	kg	30.72918425
tap water	kg	50.78502588
tempering, flat glass	kg	490
Water, well, in ground	m3	69.5
wire drawing, copper	kg	109
OUTPUTS		
Ammonia	kg	0.0223
Benzene	kg	0.0131
BOD5, Biological Oxygen Demand	kg	0.126
bus	Item(s)	1
Cadmium	kg	1.73E-06
Carbon dioxide, fossil	kg	633
Carbon monoxide, fossil	kg	0.973
Chromium	kg	2.93E-04
COD, Chemical Oxygen Demand	kg	0.126
Copper	kg	2.93E-04
Dinitrogen monoxide	kg	0.0223
DOC, Dissolved Organic Carbon	kg	0.0551
Lead	kg	1.90E-08
Mercury	kg	3.45E-09
Methane, fossil	kg	0.0165
Nickel	kg	1.21E-05
Nitrogen oxides	kg	6

NMVOC, non-methane volatile organic compounds, unspecified origin	kg	7.87
Particulates, < 2.5 um	kg	0.254
Particulates, > 10 um	kg	0.0109
Particulates, > 2.5 um, and < 10um	kg	0.0212
Selenium	kg	1.73E-06
Sulfur dioxide	kg	0.12
TOC, Total Organic Carbon	kg	0.0551
Toluene	kg	0.00551
wastewater from lorry production	m3	2.18
wastewater, average	m3	15.9
Water	m3	12.885
Water	m3	54.935
Xylene	kg	0.00551
Zinc	kg	1.73E-04
DISTRIBUTION		
INPUTS		
transport, freight, lorry >32 metric ton, EURO4	t*km	11308
transport, freight, lorry >32 metric ton, EURO4	t*km	701.8
transport, freight, sea, container ship	t*km	101068.22
OUTPUTS		
transportation of regular bus	Item(s)	1
USAGE AND MAINTENANCE		
INPUTS		
diesel, low-sulfur	kg	5.01E-05
diesel, low-sulfur	kg	7.48E-04
diesel, low-sulfur	kg	3.39E-04
diesel, low-sulfur	kg	0.01803811
diesel, low-sulfur	kg	0.00354469
diesel, low-sulfur	kg	7.56E-04
diesel, low-sulfur	kg	0.00151066
maintenance, bus	Item(s)	7.14E-08
road	m*a	4.57E-04
road maintenance	m*a	8.67E-05
OUTPUTS		
Acetaldehyde	kg	2.99E-06

Ammonia	kg	3.57E-07
Benzene	kg	2.15E-07
Cadmium	kg	2.65E-10
Cadmium	kg	1.27E-10
Cadmium, ion	kg	1.27E-10
Carbon dioxide, fossil	kg	0.07889333
Carbon monoxide, fossil	kg	2.30E-04
Chromium	kg	1.66E-09
Chromium	kg	6.05E-10
Chromium VI	kg	2.50E-12
Chromium, ion	kg	6.05E-10
Copper	kg	7.04E-08
Copper	kg	8.50E-09
Copper, ion	kg	8.50E-09
Dinitrogen monoxide	kg	9.44E-07
Formaldehyde	kg	5.50E-06
Lead	kg	2.02E-09
Lead	kg	5.22E-09
Lead	kg	5.22E-09
Mercury	kg	5.00E-13
Methane, fossil	kg	1.61E-06
Nickel	kg	2.11E-09
Nickel	kg	1.64E-09
Nickel, ion	kg	1.64E-09
Nitrogen oxides	kg	9.17E-04
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	5.35E-05
PAH, polycyclic aromatic hydrocarbons	kg	2.86E-11
Particulates, < 2.5 um	kg	3.17E-05
Particulates, > 10 um	kg	4.05E-06
Particulates, > 2.5 um, and < 10um	kg	4.40E-06
Selenium	kg	2.50E-10
Sulfur dioxide	kg	2.50E-06
Toluene	kg	1.12E-06
transport, regular bus	p*km	1
Xylene	kg	5.37E-07

Zinc	kg	5.32E-08
Zinc	kg	3.58E-07
Zinc, ion	kg	3.58E-07
END OF LIFE		
INPUTS		
Used bus	Item(s)	1
OUTPUTS		
waste emulsion paint	kg	10.9662725
waste emulsion paint	kg	1.03372752
waste glass	kg	0.12052962
waste glass	kg	9.23014923
waste glass	kg	86.9862394
waste glass	kg	0.35515701
waste glass	kg	0.01930004
waste glass	kg	0.07937121
waste glass	kg	17.3585307
waste glass	kg	0.85072285
waste mineral oil	kg	6.96450501
waste mineral oil	kg	18.235495
waste plastic, mixture	kg	4.11031196
waste plastic, mixture	kg	1.61213061
waste plastic, mixture	kg	61.5167479
waste plastic, mixture	kg	430.651265
waste plastic, mixture	kg	0.31085621
waste plastic, mixture	kg	0.68585385
waste plastic, mixture	kg	1.69770605
waste plastic, mixture	kg	52.4151283

Table S2. Proposed fleet for cars and motorcycles of Scenario 3.

Vehicle	Current fleet (vehicles)	Current modal shares by vehicle type	Fleet in Scenario 3	Modal shares in Scenario 3
Petrol car	49,534	99.18%	24,777	49.61%
Diesel car	392	0.78%	196	0.39%

Electric car	20	0.04%	24,973	50.00%
Total cars	**49,946**	**100.00%**	**49,946**	**100%**
Conventional scooter	125,314	99.99%	62,665	50%
Electric scooter	16	0.01%	62,665	50%
Total scooters	**125,330**	**100.00%**	**125,330**	**100%**

Table S3. Energy mix in the market for electricity in Colombia: current mix versus the 100% renewable

Scenario 0: current energy mix in the market for electricity in Colombia (ecoinvent 3.8)	
Provider	**%**
market for electricity, high voltage | electricity, high voltage | Cutoff, U - CO	3.97%
heat and power co-generation, biogas, gas engine | electricity, high voltage | Cutoff, U - RoW	**0.00%**
electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - CO	0.94%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U - CO	**76.82%**
electricity production, oil | electricity, high voltage | Cutoff, U - CO	0.22%
electricity, high voltage, import from VE | electricity, high voltage | Cutoff, U - CO	0.17%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CO	4.80%
electricity production, hydro, run-of-river | electricity, high voltage | Cutoff, U - CO	**6.10%**
electricity production, natural gas, combined cycle power plant | electricity, high voltage | Cutoff, U - CO	6.91%
electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | Cutoff, U - CO	**0.06%**
Total of renewable energy	**82.98%**
Scenario 4: 100% renewable energy mix in the market for electricity in Colombia (ecoinvent 3.8)	
Provider	**%**
market for electricity, high voltage | electricity, high voltage | Cutoff, U - CO	0.00%
heat and power co-generation, biogas, gas engine | electricity, high voltage | Cutoff, U - RoW	0.01%
electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - CO	0.00%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U - CO	92.57%
electricity production, oil | electricity, high voltage | Cutoff, U - CO	0.00%
electricity, high voltage, import from VE | electricity, high voltage | Cutoff, U - CO	0.00%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CO	0.00%
electricity production, hydro, run-of-river | electricity, high voltage | Cutoff, U - CO	7.35%
electricity production, natural gas, combined cycle power plant | electricity, high voltage | Cutoff, U - CO	0.00%
electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | Cutoff, U - CO	0.07%

market for transmission network, electricity, high voltage | transmission network, electricity, high voltage | Cutoff, U - GLO	0.00%
market for transmission network, long-distance | transmission network, long-distance | Cutoff, U - GLO	0.00%
Total of renewable energy	**100.00%**

Table S4. Average travelled distances and daily trips proposed for Scenario 8.

Vehicle	Current average travelled distance (km·journey^{-1})	Average travelled distance in Scenario 8 (km·journey^{-1})	Current average of daily journeys (journeys·day^{-1})	Average of daily journeys in Scenario 8 (journeys·day^{-1})
Petrol car	9.64	4.82	2.01	1.01
Diesel car	9.64	4.82	2.01	1.01
Electric car	9.64	4.82	2.01	1.01
Conventional scooter	8.72	4.36	1.09	0.55
Electric scooter	8.72	4.36	1.09	0.55
Electric bike	6.20	3.10	0.39	0.20
Conventional bike	6.20	3.10	0.39	0.20
Bus	9.15	9.15	1.71	0.85

Table S5. Population and transport modal share in each simulated scenario

Population by means of transport (inhabitants)									
Vehicle	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**
Petrol car	61673	0	51040	30849	30849	61673	61673	16482	61673
Diesel car	488	62161	404	244	244	488	488	130	488
Electric car	25	25	21	31093	31093	25	25	7	25
Conventional scooter	83619	83619	72899	41815	41815	83619	83619	38057	83619
Electric scooter	11	11	9	41815	41815	11	11	5	11
Electric bike	1250	1250	6248	1250	1250	1250	1250	1250	1250
Conventional bike	4111	4111	20557	4111	4111	4111	4111	4111	4111
Bus	182270	182270	182270	182270	182270	182270	182270	273404	182270
Rest of Population (RoP)	202641	202641	202641	202641	202641	202641	202641	202641	202641
Total	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**
Modal share (% inhabitants)									
Vehicle	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**

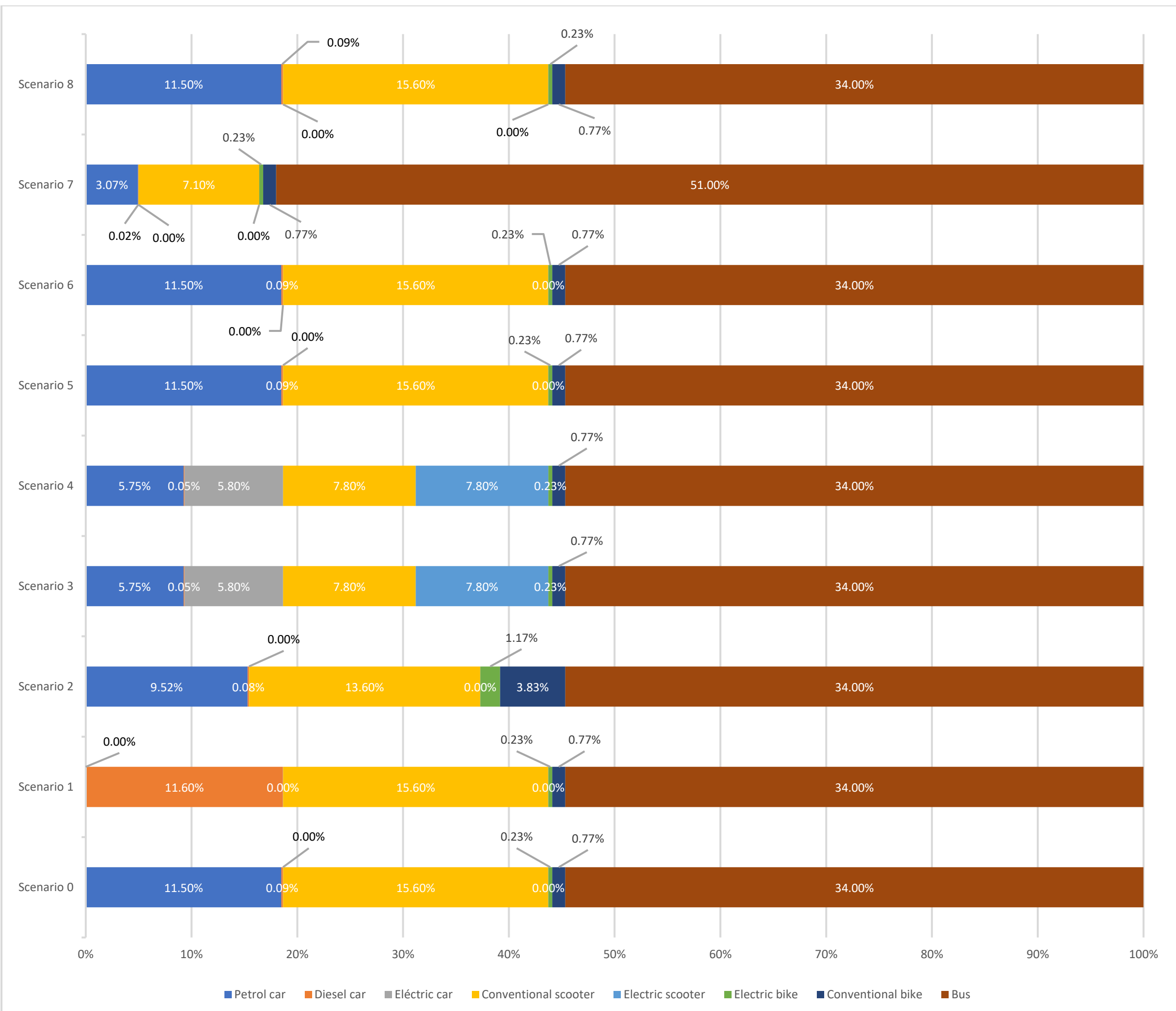
Petrol car	11.50%	0.00%	9.52%	5.75%	5.75%	11.50%	11.50%	3.07%	11.50%
Diesel car	0.09%	11.60%	0.08%	0.05%	0.05%	0.09%	0.09%	0.02%	0.09%
Electric car	0.00%	0.00%	0.00%	5.80%	5.80%	0.00%	0.00%	0.00%	0.00%
Conventional scooter	15.60%	15.60%	13.60%	7.80%	7.80%	15.60%	15.60%	7.10%	15.60%
Electric scooter	0.00%	0.00%	0.00%	7.80%	7.80%	0.00%	0.00%	0.00%	0.00%
Electric bike	0.23%	0.23%	1.17%	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%
Conventional bike	0.77%	0.77%	3.83%	0.77%	0.77%	0.77%	0.77%	0.77%	0.77%
Bus	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%	51.00%	34.00%
Rest of Population (RoP)	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Table S6. Population and transport modal share in each variation of Scenario 7

Population by means of transport in Scenario 7 (inhabitants)									
Vehicle	**Sc. 0**	**Sc. 7 (+50%)**	**Sc.7 (+52%)**	**Sc. 7 (+54%)**	**Sc.7 (+56%)**	**Sc. 7 (+58%)**	**Sc.7 (+60%)**	**Sc. 7 (+70%)**	**Sc.7 (+80%)**
Petrol car	61673	16482	14674	12866	11059	9251	7443	7443	0
Diesel car	488	130	116	102	88	73	59	59	0
Eléctric car	25	7	6	5	4	4	3	3	0
Conventional scooter	83619	38057	36235	34412	32590	30767	28945	10720	0
Electric scooter	11	5	5	4	4	4	4	1	0
Electric bike	1250	1250	1250	1250	1250	1250	1250	1250	1250
Conventional bike	4111	4111	4111	4111	4111	4111	4111	4111	4111
Bus	182270	273404	277050	280695	284341	287986	291631	309858	328085
Rest of Population (RoP)	202641	202641	202641	202641	202641	202641	202641	202641	202641
Total	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**	**536087**
Modal share in Scenario 7 (% inhabitants)									
Vehicle	**Sc. 0**	**Sc. 7 (+50%)**	**Sc.7 (+52%)**	**Sc. 7 (+54%)**	**Sc.7 (+56%)**	**Sc. 7 (+58%)**	**Sc.7 (+60%)**	**Sc. 7 (+70%)**	**Sc.7 (+80%)**
Petrol car	11.50%	3.07%	2.74%	2.40%	2.06%	1.73%	1.39%	1.39%	0.00%
Diesel car	0.09%	0.02%	0.02%	0.02%	0.02%	0.01%	0.01%	0.01%	0.00%
Eléctric car	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Conventional scooter	15.60%	7.10%	6.76%	6.42%	6.08%	5.74%	5.40%	2.00%	0.00%
Electric scooter	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Electric bike	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%
Conventional bike	0.77%	0.77%	0.77%	0.77%	0.77%	0.77%	0.77%	0.77%	0.77%
Bus	34.00%	51.00%	51.68%	52.36%	53.04%	53.72%	54.40%	57.80%	61.20%
Rest of Population (RoP)	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%	37.80%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

Figure S1. Transport modal share in each simulated scenario.



Supporting Information for:

Optimal replacement scenarios for an average petrol passenger car using life cycle assessment

Table S1. Inventory data for the LCA of the analysed EURO 3 petrol car obtained from Ecoinvent 3.9.

INPUTS		
Flow	**Amount**	**Unit**
passenger car maintenance	6.45E-06	Item(s)
passenger car, petrol/natural gas	0.008	kg
petrol, low-sulfur	0.00108118	kg
petrol, low-sulfur	0.05672561	kg
road	6.97E-04	m*a
road maintenance	2.65E-04	m*a
OUTPUTS		
Flow	**Amount**	**Unit**
1-Pentene	2.44E-08	kg
2-Methylpentane	7.42E-06	kg
Acetaldehyde	1.67E-07	kg
Acetone	1.35E-07	kg
Acrolein	4.22E-08	kg
Ammonia	1.73E-06	kg
Benzaldehyde	4.88E-08	kg
Benzene	3.70E-06	kg
brake wear emissions, passenger car	5.77E-06	kg
Butane	7.36E-06	kg
Cadmium II	5.78E-10	kg
Carbon dioxide, fossil	0.1838256	kg
Carbon monoxide, fossil	0.001216	kg
Chromium III	2.89E-09	kg
Chromium VI	5.78E-12	kg

Copper ion	9.83E-08	kg
Cyclohexane (for all cycloalkanes)	2.53E-07	kg
Dinitrogen monoxide	7.51E-06	kg
Ethane	1.03E-06	kg
Ethylene	2.65E-08	kg
Ethylene oxide	1.62E-06	kg
Formaldehyde	3.77E-07	kg
Heptane	1.64E-07	kg
Hexane	3.57E-07	kg
Lead II	8.67E-11	kg
m-Xylene	3.17E-06	kg
Mercury II	4.05E-12	kg
Methane, fossil	2.85E-05	kg
Methyl ethyl ketone	1.11E-08	kg
Nickel II	4.05E-09	kg
Nitrogen oxides	7.16E-05	kg
NMVOC, non-methane volatile organic compounds	6.65E-05	kg
o-Xylene	7.37E-07	kg
PAH, polycyclic aromatic hydrocarbons	2.01E-09	kg
Particulate Matter, < 2.5 um	1.01E-06	kg
Pentane	8.65E-06	kg
Propane	5.59E-06	kg
Propene	1.48E-07	kg
Propylene oxide	8.48E-07	kg
road wear emissions, passenger car	1.27E-05	kg
Selenium IV	5.78E-10	kg
Styrene	2.24E-07	kg
Sulfur dioxide	1.16E-06	kg
Toluene	7.33E-06	kg
transport, passenger car, small size, petrol, EURO 3	1	km

tyre wear emissions, passenger car	7.43E-05	kg
Zinc II	5.78E-08	kg

Table S2. Inventory data for the LCA of the analysed EURO 5 petrol car obtained from Ecoinvent 3.9.

INPUTS		
Flow	**Amount**	**Unit**
passenger car maintenance	6.45E-06	Item(s)
passenger car, petrol/natural gas	0.008	kg
petrol, low-sulfur	9.42E-04	kg
petrol, low-sulfur	0.04940514	kg
road	6.97E-04	m*a
road maintenance	2.65E-04	m*a
OUTPUTS		
Flow	**Amount**	**Unit**
1-Pentene	1.96E-08	kg
2-Methylpentane	7.42E-06	kg
Acetaldehyde	1.33E-07	kg
Acetone	1.09E-07	kg
Acrolein	3.38E-08	kg
Ammonia	1.51E-06	kg
Benzaldehyde	3.91E-08	kg
Benzene	3.38E-06	kg
brake wear emissions, passenger car	5.77E-06	kg
Butane	7.13E-06	kg
Cadmium II	5.03E-10	kg
Carbon dioxide, fossil	0.1601028	kg
Carbon monoxide, fossil	3.66E-04	kg
Chromium III	2.52E-09	kg
Chromium VI	5.03E-12	kg

Copper ion	8.56E-08	kg
Cyclohexane (for all cycloalkanes)	2.03E-07	kg
Dinitrogen monoxide	6.55E-06	kg
Ethane	8.85E-07	kg
Ethylene	2.65E-08	kg
Ethylene oxide	1.30E-06	kg
Formaldehyde	3.02E-07	kg
Heptane	1.32E-07	kg
Hexane	2.86E-07	kg
Lead II	7.55E-11	kg
m-Xylene	3.07E-06	kg
Mercury II	3.52E-12	kg
Methane, fossil	1.36E-05	kg
Methyl ethyl ketone	8.89E-09	kg
Nickel II	3.52E-09	kg
Nitrogen oxides	2.93E-05	kg
NMVOC, non-methane volatile organic compounds	6.45E-05	kg
o-Xylene	6.93E-07	kg
PAH, polycyclic aromatic hydrocarbons	1.75E-09	kg
Particulate Matter, < 2.5 um	1.00E-06	kg
Pentane	8.55E-06	kg
Propane	5.56E-06	kg
Propene	1.48E-07	kg
Propylene oxide	6.80E-07	kg
road wear emissions, passenger car	1.27E-05	kg
Selenium IV	5.03E-10	kg
Styrene	1.80E-07	kg
Sulfur dioxide	1.01E-06	kg
Toluene	7.09E-06	kg
transport, passenger car, small size, petrol, EURO 5	1	km

tyre wear emissions, passenger car	7.43E-05	kg
Zinc II	5.03E-08	kg

Table S3. Inventory data for the LCA of the analysed EURO 5 diesel car obtained from Ecoinvent 3.9.

INPUTS		
Flow	**Amount**	**Unit**
diesel, low-sulfur	0.04344796	kg
passenger car maintenance	6.45E-06	Item(s)
passenger car, diesel	0.008	kg
road	6.97E-04	m*a
road maintenance	2.65E-04	m*a
OUTPUTS		
Flow	**Amount**	**Unit**
Acetaldehyde	1.08E-06	kg
Acetone	4.92E-07	kg
Acrolein	5.99E-07	kg
Ammonia	6.95E-07	kg
Benzaldehyde	1.44E-07	kg
Benzene	3.31E-07	kg
brake wear emissions, passenger car	5.77E-06	kg
Butane	1.84E-08	kg
Cadmium II	4.34E-10	kg
Carbon dioxide, fossil	0.13642659	kg
Carbon monoxide, fossil	5.83E-05	kg
Chromium III	2.17E-09	kg
Chromium VI	4.34E-12	kg
Copper ion	7.39E-08	kg
Cyclohexane (for all cycloalkanes)	1.09E-07	kg
Dinitrogen monoxide	2.17E-06	kg

Ethane	5.52E-08	kg
Ethylene oxide	1.84E-06	kg
Formaldehyde	2.01E-06	kg
Heptane	3.35E-08	kg
Lead II	3.58E-15	kg
m-Xylene	1.02E-07	kg
Mercury II	8.69E-13	kg
Methane, fossil	1.75E-06	kg
Methyl ethyl ketone	2.01E-07	kg
Nickel II	3.04E-09	kg
Nitrogen oxides	6.67E-04	kg
NMVOC, non-methane volatile organic compounds	8.87E-06	kg
o-Xylene	4.52E-08	kg
PAH, polycyclic aromatic hydrocarbons	8.01E-09	kg
Particulate Matter, < 2.5 um	1.91E-06	kg
Pentane	6.69E-09	kg
Propane	1.84E-08	kg
Propylene oxide	6.02E-07	kg
road wear emissions, passenger car	1.27E-05	kg
Selenium IV	4.34E-10	kg
Styrene	6.19E-08	kg
Sulfur dioxide	8.69E-07	kg
Toluene	1.15E-07	kg
transport, passenger car, small size, diesel, EURO 5	1	km
tyre wear emissions, passenger car	7.43E-05	kg
Zinc II	4.34E-08	kg

Table S4. Inventory data for the LCA of the analysed electric cars obtained from Ecoinvent 3.9.

INPUTS		
Flow	**Amount**	**Unit**
battery, Li-ion, LiMn2O4, rechargeable, prismatic	0.00262	kg
electricity, low voltage	0.199	kWh
maintenance, passenger car, electric, without battery	6.67E-06	Item(s)
passenger car, electric, without battery	0.00612147	kg
road	4.87E-04	m*a
OUTPUTS		
Flow	**Amount**	**Unit**
brake wear emissions, passenger car	1.05E-06	kg
road wear emissions, passenger car	1.16E-05	kg
transport, passenger car, electric	1	km
tyre wear emissions, passenger car	6.76E-05	kg
used Li-ion battery	0.00262	kg

Table S5. Current energy mix in the Spanish market for electricity, obtained from Ecoinvent 3.9.

Flow	Amount	Unit	Provider
electricity, high voltage	1.50E-01	kWh	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	3.79E-03	kWh	electricity production, lignite | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	3.80E-02	kWh	electricity production, oil | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	3.74E-02	kWh	market for electricity, high voltage | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	5.42E-02	kWh	electricity, high voltage, import from FR | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	9.34E-03	kWh	electricity production, hydro, pumped storage | electricity, high voltage | Cutoff, U - ES

electricity, high voltage	1.32E-03	kWh	heat and power co-generation, biogas, gas engine | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	3.98E-04	kWh	electricity production, wind, >3MW turbine, onshore | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	4.72E-04	kWh	electricity production, solar tower power plant, 20 MW | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	5.11E-03	kWh	electricity, high voltage, import from MA | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	3.38E-02	kWh	electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	3.84E-03	kWh	treatment of blast furnace gas, in power plant | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	4.72E-02	kWh	electricity production, hard coal | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	1.86E-01	kWh	electricity production, nuclear, pressure water reactor | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	6.84E-03	kWh	electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	6.57E-02	kWh	electricity production, hydro, run-of-river | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	4.63E-02	kWh	electricity production, nuclear, boiling water reactor | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	2.09E-02	kWh	electricity production, solar thermal parabolic trough, 50 MW | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	1.04E-02	kWh	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	8.24E-02	kWh	electricity production, wind, <1MW turbine, onshore | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	2.13E-01	kWh	electricity production, natural gas, combined cycle power plant | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	1.99E-02	kWh	electricity, high voltage, import from PT | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	7.33E-04	kWh	treatment of coal gas, in power plant | electricity, high voltage | Cutoff, U - ES
electricity, high voltage	4.52E-05	kWh	electricity production, wind, 1-3MW turbine, offshore | electricity, high voltage | Cutoff, U - ES

transmission network, electricity, high voltage direct current aerial line	4.95E-09	km	market for transmission network, electricity, high voltage direct current aerial line | transmission network, electricity, high voltage direct current aerial line | Cutoff, U - GLO
transmission network, electricity, high voltage direct current land cable	1.30E-10	km	market for transmission network, electricity, high voltage direct current land cable | transmission network, electricity, high voltage direct current land cable | Cutoff, U - GLO
transmission network, electricity, high voltage direct current subsea cable	1.02E-10	km	market for transmission network, electricity, high voltage direct current subsea cable | transmission network, electricity, high voltage direct current subsea cable | Cutoff, U - GLO

Table S6. Contribution trees of the analysed vehicles

Phase	**Petrol EURO 3**	**Petrol EURO 5**	**Diesel EURO 5**	**Electric (ES)**	**Electric (RER)**	**Electric (GLO)**	**Electric 100% renewable**
Manufacture + EOL	17.55%	19.50%	22.36%	51.03%	46.09%	31.12%	75.58%
Exhaust pipe	57.24%	55.26%	52.77%	0.00%	0.00%	0.00%	0.00%
Fuel	19.34%	18.71%	17.47%	39.34%	45.21%	63.00%	10.15%
Road maintenance	3.65%	4.06%	4.60%	5.06%	4.57%	3.09%	7.50%
Vechicle maintenance	2.22%	2.47%	2.80%	4.57%	4.13%	2.79%	6.77%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table S7. Cumulative Energy Demand (CED) related to each scenario

Scenario	**Amount**	**Unit**	**Reduction**
0	156,782.29	kwh-eq·p^{-1}	-
1	142,015.97	kwh-eq·p^{-1}	9.42%
2	131,869.79	kwh-eq·p^{-1}	15.89%
3	114,697.92	kwh-eq·p^{-1}	26.84%
4	81,065.63	kwh-eq·p^{-1}	48.29%
5	43,235.00	kwh-eq·p^{-1}	72.42%

Table S8. PM 2.5 analysis results and replacement year for the simulated scenarios

Scenario	Embodied PM2.5 g PM2.5 -eq	Operational PM2.5 g PM2.5 -eq	PM2.5 savings in usage g PM2.5 -eq·pkm⁻¹	Total PM2.5 savings in usage g PM2.5 -eq	Savings ratio at end-of-life %	Year to replace
0	2.38E+04	2.42E+04	-	-	-	-
1	2.43E+04	2.17E+04	0.01	2.44E+03	-894.55%	158.33
2	2.45E+04	3.15E+04	-0.02	-7.32E+03	No feasible savings	No feasible replacement
3	4.63E+04	3.10E+04	-0.02	-6.84E+03	No feasible savings	No feasible replacement
4	4.61E+04	1.52E+04	0.03	8.94E+03	-415.52%	82.07
5	4.61E+04	1.52E+04	0.05	3.01E+04	-53.09%	24.37

Figure S1. Scope and functional unit for the Life-Cycle Assessments.

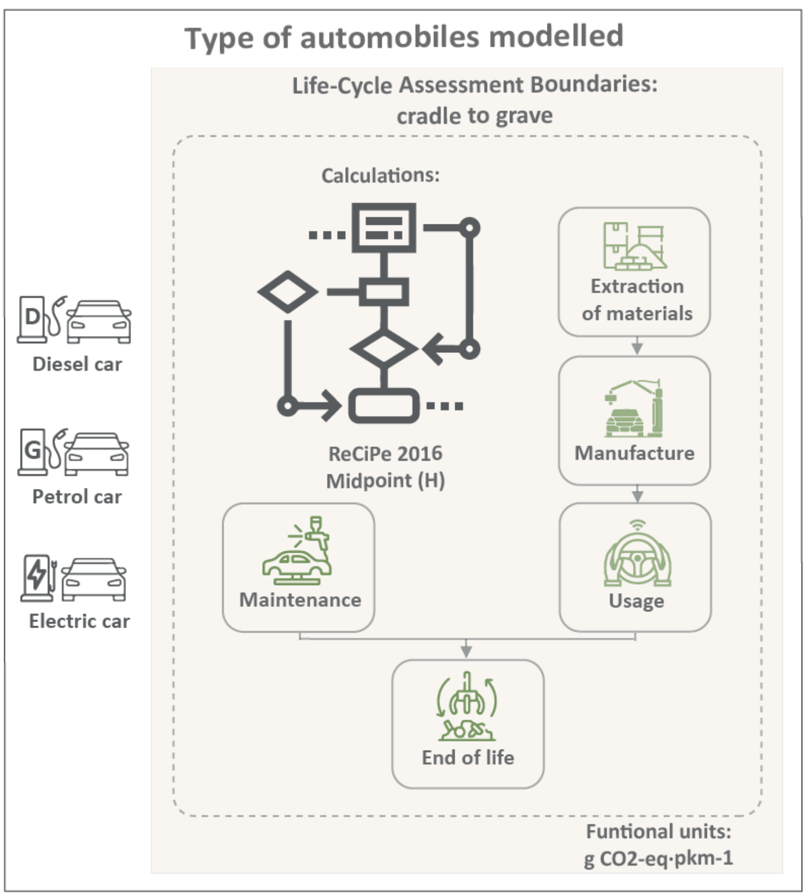


Figure S2. Comparison of GWP of analysed vehicles.