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Dynamic Evaluation of Environmental Effects Associated with the Inclusion of Hydrogen-powered Vehicles in Colombia

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ABSTRACT

Currently, the generation of CO_2 emissions into the environment has increased due to the use of fossil fuels by the transportation sector and other economic sectors, motivating governments to propose mitigation actions. As a result, the search for zero-emission transportation alternatives has gained momentum, with Hydrogen technology being one of the promising solutions due to its clean and efficient energy source. In compliance with this, the Hydrogen roadmap was developed in Colombia, which seeks to encourage the use of hydrogen as a fuel and energy generator in the country. In this study, the current composition of the vehicle fleet was characterized, then a dynamic simulation model was constructed for the replacement of fossil fuel vehicles with zero-emission vehicles, considering the particularities of the country, to finally analyze the generation of CO_2 in the vehicle fleet from different scenarios related to the policies proposed by the government of Colombia and stipulated in the roadmap of hydrogen. With this, it was possible to demonstrate the positive impact of taking measures for vehicle replacement in the long term. Additionally, the model could be employed in other countries, considering the particularities of the vehicle fleet and the regulations specific to the regions.

Keywords: CO_2, Hydrogen, Vehicle Fleet, The Roadmap of Hydrogen
JEL Classifications: C63, Q42, Q51, R42.

1. INTRODUCTION

In recent years, a phenomenon has been occurring aimed at increasing temperatures, especially in the last two decades, where the ten warmest average temperatures in the world have been recorded. According to the World Climate Report 2020, conducted by the National Oceanic and Atmospheric Administration (National Centers for Environmental Information [NCEI] 2020), each year since 2013 has consistently ranked within this list. As a result of the risks associated with climate change, several countries are now actively pursuing the development of innovative strategies and approaches to swiftly reduce greenhouse gas emissions (GHG) (Holmatov and Hoekstra 2020).

For Colombia, carbon dioxide (CO_2) is the most impactful greenhouse gas, generated by various sectors including energy generation, construction, industries, agriculture, and the transportation sector. Notably, the transportation sector alone contributes 24.7% to the total CO_2 emissions (CEPSA, 2015). Within this sector, land transportation is responsible for 74% of emissions, and CO_2 emissions from transportation have increased by 71% between 1990 and 2016 (IEA, 2018).

To mitigate these emissions, clean technologies have been introduced in the form of electric vehicles and hydrogen combustion vehicles (H_2), among others (Earl et al., 2018). Clean technologies refer to the use of electricity or hydrogen obtained from renewable sources (Holmatov and Hoekstra 2020) (Rubin and Chester 2013). In line with this, the Colombian government, in pursuit of the national energy plan "Ideario 2050," has enacted laws and policies to reduce CO_2 emissions. For instance, Law 1964 of 2019 mandates the replacement of mass transportation systems with zero-emission vehicles in cities by 2030 (UPME, 2015).

Hydrogen (H_2) is a highly promising alternative energy source due to its numerous virtues. It serves as an energy carrier, can be stored in facilities of different sizes (small, medium, and large), and has charging times comparable to fossil-fuel vehicles (Morlanes, 2008) (Ibáñez et al., 2020). Recognizing these benefits, the Colombian government has presented the Hydrogen Roadmap, aimed at facilitating the country's energy transition and reducing CO_2 emissions (Ministerio de Minas y Energía República de Colombia, 2020).

It is evident in different studies from countries such as Denmark (Lund and Mathiesen, 2009) and Croatia (Krajačić et al., 2011), the analysis of energy systems integrating clean technology fuels, finding the best composition of said integration for the years 2030. and 2050, these studies did not include vehicles, which represents an important aspect to consider.

Also, it was found that system dynamics is a tool that allows for studying complex systems over time and managing feedback systems such as those observed in politics and economics (Veziroğlu and Macário, 2014). In particular, system dynamics has been used for the analysis of transitions from petrol vehicles to hydrogen vehicles, presenting qualitative and quantitative scenarios for the said technology transition in the UK, as outlined in (McDowall, 2014). Likewise, system dynamics has also been used for the comparative analysis between the transition paths of electricity, biofuels, and hydrogen for Iceland as set out in (Shafiei et al., 2015).

Therefore, this study analyzes how the CO_2 emissions of the Colombian vehicle fleet would behave if H_2 combustion vehicles are included, considering compliance with the law on obsolescence, through analysis with system dynamics. It was found that applying any of the proposed scenarios there is a minimum CO_2 reduction of 54.4% and a maximum of 90% in the year 2050. The article begins with the characterization of the Colombian automobile fleet and the main environmental indicators that exist in Afterwards, the dynamic simulation model is created in the Vesim software with its respective validation, followed by the approach of different scenarios where clean technology vehicles are included to carry out a comparative analysis between the results of each of the scenarios and by Lastly, the conclusions of the study are generated.

2. METHODOLOGY

This study was conducted in three phases. In the first phase, the Colombian automotive fleet was characterized by conducting a literature review. This review provided information on the composition of the fleet, GHG emissions, fuel consumption, and the age distribution of vehicles. In the second phase, a dynamic simulation model was developed, specifically tailored to the unique characteristics of Colombia. This model aimed to generate strategies and proposals for the integration of zero-emission vehicles. In the third phase, various scenarios for the inclusion of H_2 vehicles within the Colombian automotive fleet were proposed. Based on these scenarios, the environmental impacts associated with the introduction of these vehicles were evaluated.

2.1. Characterization of the Automotive Fleet in Colombia

The automotive fleet in Colombia refers to vehicles that are actively in use on the country's roads (Ontiveros Lajo 2018). It can be classified into private and public service vehicles, with private service accounting for 82% of the fleet, while public service vehicles make up the remaining 18% (RUNT, 2020).

Regarding the age distribution of the Colombian automobile fleet, the average age of the automobile fleet in Colombia is 16 years, this is because approximately 33% of the vehicles in circulation are more than 20 years old, a percentage that continues to grow due to to the Tendency of purchasing used cars among the population (Máter et al., 2018). According to Law 105 of 1993 in Colombia, public transport vehicles can be replaced after 20 years from their manufacturing date, with the possibility of a 10-year extension if the vehicle undergoes any modifications (MinTransporte, 1993).

Fossil fuels power 99% of the automotive fleet in Colombia (RUNT, 2020). According to Rojas et al., poor air quality, which contains particulate matter and black carbon, is a significant cause of mortality and morbidity in Colombian cities. This pollution is primarily generated by the combustion of fossil fuels in the automotive fleet, responsible for over 80% of emissions (Rojas et al. 2019). It is important to consider that the amount of emissions produced by a vehicle depends on factors such as fuel quality, engine condition, and age (Méndez Montoya, 2017).

Colombia currently lacks a National Plan for Improving Air Quality that would bring about significant policy changes regarding fossil fuels and enable the swift implementation of new technologies to address this issue (Rojas et al., 2019). Despite the ongoing energy transition, the oil sector in Colombia anticipates a 3% growth in demand for fossil fuels until 2030, as these fuels are expected to remain the country's primary energy source (ACP, 2020).

Therefore, the developed model considers the unique characteristics of the Colombian automotive fleet to provide an initial framework for the development of strategies for the integration of hydrogen vehicles in Colombia. However, the model can also be customized to accommodate specific conditions in other countries and regions, enabling the exploration of scenarios related to policy evaluation, automotive fleet decisions, and their environmental effects.

2.2. Causal Loop Diagram

The following is a representation of the study system using the influence diagram as a resource, created using the Vensim program. The main variables such as the vehicle fleet, obsolescence, vehicle replacement, fossil fuel demand, and CO_2 emissions, among others, are identified. The blue lines show a positive relationship, and the red lines show a negative relationship between the variables. The relationships between these variables form balancing (B) and reinforcing (R) feedback loops. The influence diagram of the model has 5 balancing loops and 3 reinforcing loops, which will be explained in detail below (Figure 1).

2.2.1. Balancing loops

The B1 balancing loop illustrates a causal relationship between population growth, economic growth, the expansion of the automotive fleet, CO2 emissions, air pollution, public health, and population decrease (Figure 2). It is supported by the econometric analysis conducted by (Soloaga et al., 2016),

Figure 1: Causal loop diagram

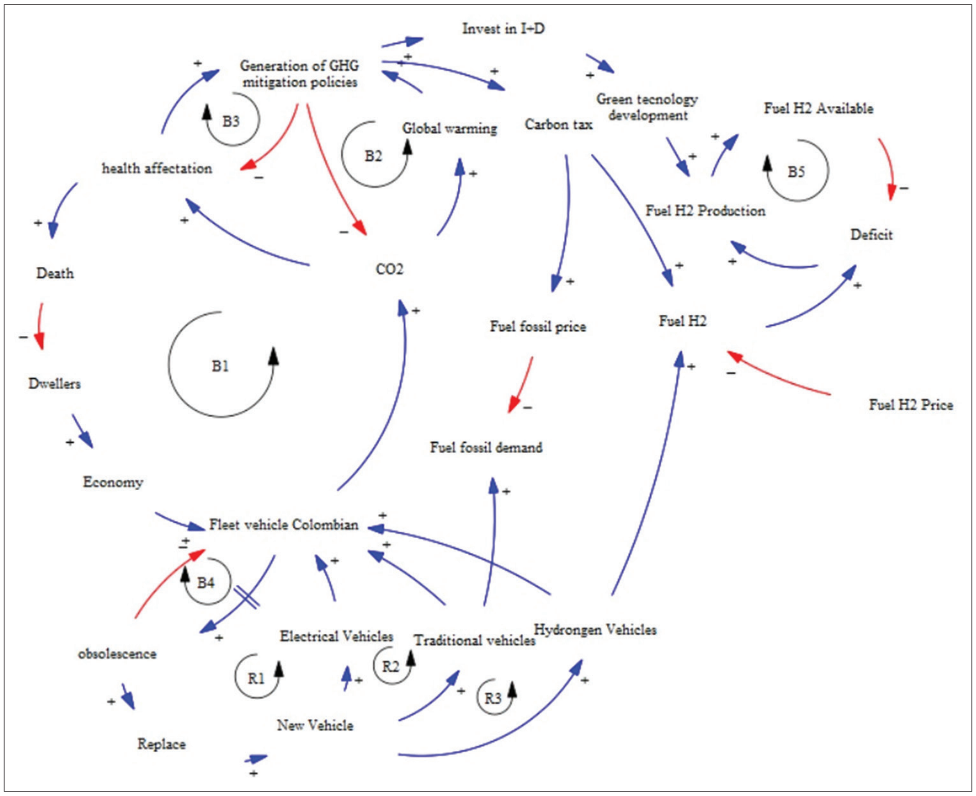


Figure 2: Balancing loop C1

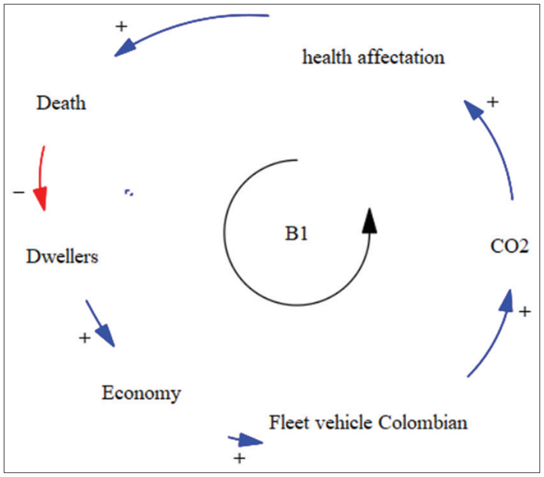
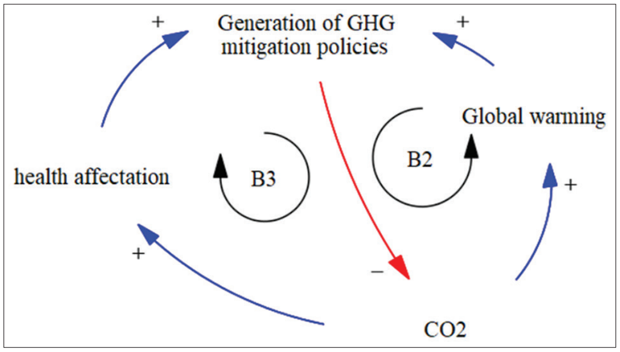


Figure 3: Balancing loops B2 y B3



which found a positive correlation between population growth and economic growth. According to the B1 loop, an increase in population leads to economic growth (Orlandini and Salamanca, 2020). This, in turn, results in an expansion of the automotive fleet, contributing to higher CO_2 emissions. The increased emissions lead to air pollution, negatively impacting public health and resulting in deaths, ultimately causing a decrease in the population.

In loops B2 and B3 (Figure 3), it is indicated that the increase in CO_2 emissions generates an accumulation of gases in the atmosphere, contributing to the increase in global warming. This leads to the country developing policies for the mitigation of GHG emissions. If these mitigation policies are effective, over time, there will be fewer emissions of CO_2 into the environment.

The Balancing loop B4 (Figure 4) shows the effect of obsolescence within the vehicle fleet, where current vehicles become obsolete over time. On the other hand, the reinforcing loops R1, R2, and R3 show that the higher the obsolescence of the vehicle fleet, the greater the need for replacement, which results in more new vehicles that can be traditional, electric, or hydrogen-powered vehicles.

The B5 balancing loop (Figure 5) describes that with increased production of H_2, more H_2 becomes available as a fuel, which in turn decreases the H_2 deficit as fuel, resulting in less H_2 production.

2.3. Stock-Flow Diagram

The Stock-Flow Diagram, also known as the Forrester diagram, is constructed based on the relationships depicted in the influence diagram. It is designed to quantitatively represent the system's relationships using Equation 1 (Aracil, 1995). This diagram portrays the level variable (N) as a differential equation that considers the input and output flows at a specific time. The flows are determined by the flow variables, which reflect the changes in the level variables over time and characterize the actions within the system (Aracil, 1995). Additionally, the auxiliary variables in the system represent the intermediate steps that facilitate the calculation of each flow variable based on the given values (Ibáñez et al., 2020).

$$N(t) = N(t0) + \int_0^t (Fe - Fs)dt$$

Equation 1 Level Variable.

The Stock-Flow Diagram in this study involves the C2, C3, C4, B1, B2, B3, and B4 loops, and for greater clarity, it is divided into three parts: "Vehicle Fleet Composition," "Fuel Consumption," and "Emissions by Fuel."

2.3.1. Vehicle fleet composition

In Figure 6, the current structure of the Colombian vehicle fleet is presented, which includes 7 types of vehicles: cars, taxis, sports utility vehicle (SUVs), cargo vehicles (trucks, tractor trucks, and dump trucks), PAX (buses and minibusses), microbuses, and motorcycles. However, the latter were excluded from the study due to their low contribution to CO_2 emissions (ANDEMOS, 2017). The diagram shows the entry of new vehicles through a demand projection and the exit due to obsolescence.

Figure 4: Balancing loop B4 and reinforcing loops R1, R2 y R3

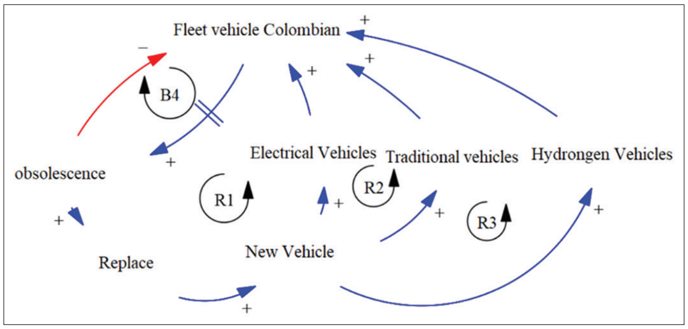
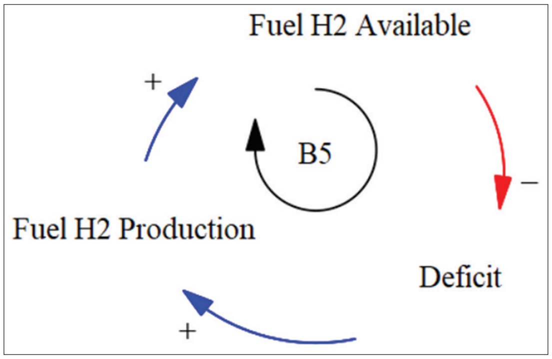


Figure 5: Balancing loop B5



2.3.2. Fuel consumption

Figures 7 and 8 present the fuel consumption for each type of vehicle since each has a different fuel efficiency per kilometer, as shown in Table 1. Additionally, the six types of vehicles travel a different number of kilometers annually on average and have different participation in terms of technology (gasoline, diesel, compressed natural gas [CNG], H_2, and electricity) (UPME et al., 2019).

2.3.3. Emissions by fuel

Figure 9 presents the part of the model in which the CO_2 emissions from the use of each fossil fuel are accumulated; they reach the flow variable "emitted CO_2" and accumulate in the stock variable "Accumulation of CO_2 emitted by fuels". For this study, as mentioned earlier, only the emissions generated by the vehicle were considered, not those produced by manufacturing each fuel type. Therefore, cars powered by electricity and hydrogen do not emit any CO_2 into the environment.

2.4. Assumptions

- For this case, the variation and volatility of the economy over the study period are excluded.
- When replacing traditional vehicles (using fossil fuels), it is assumed that there is sufficient energy and H_2 to charge zero-emission vehicles and that there will be enough charging stations available.
- Factors such as fuel prices, maintenance costs, battery replacement costs, vehicle prices, and the influence of social networks in motivating the use of these technologies are excluded.

2.5. Definition of Variables, Quantification of Parameters, and Model Validation

Tables 2-4 presents the variables used in the model with their respective units and equations that are used for model quantification. These tables show the model's relevant level, flow, and auxiliary variables with their equations and sources from which they were extracted.

Table 1: Efficiency by fuel

Type	Fuel	Km/gal	Km/m³
Automobile	Diesel	78	
	Gasoline	60	
	CNG		24
SUVs	Diesel	61	
	Gasoline	47	
	CNG		19
Taxi	Diesel	78	
	Gasoline	60	
	CNG		24
PAX	Diesel	21	
	Gasoline	16	
	CNG		6
Minibuses	Diesel	63	
	Gasoline	48	
	CNG		19
Cargo trucks	Diesel	19	
	Gasoline	15	
	CNG		7

First balance of Useful Energy for Colombia and Quantification of related energy losses and the energy efficiency gap (UPME et al. 2019)

Figure 6: Vehicle fleet composition

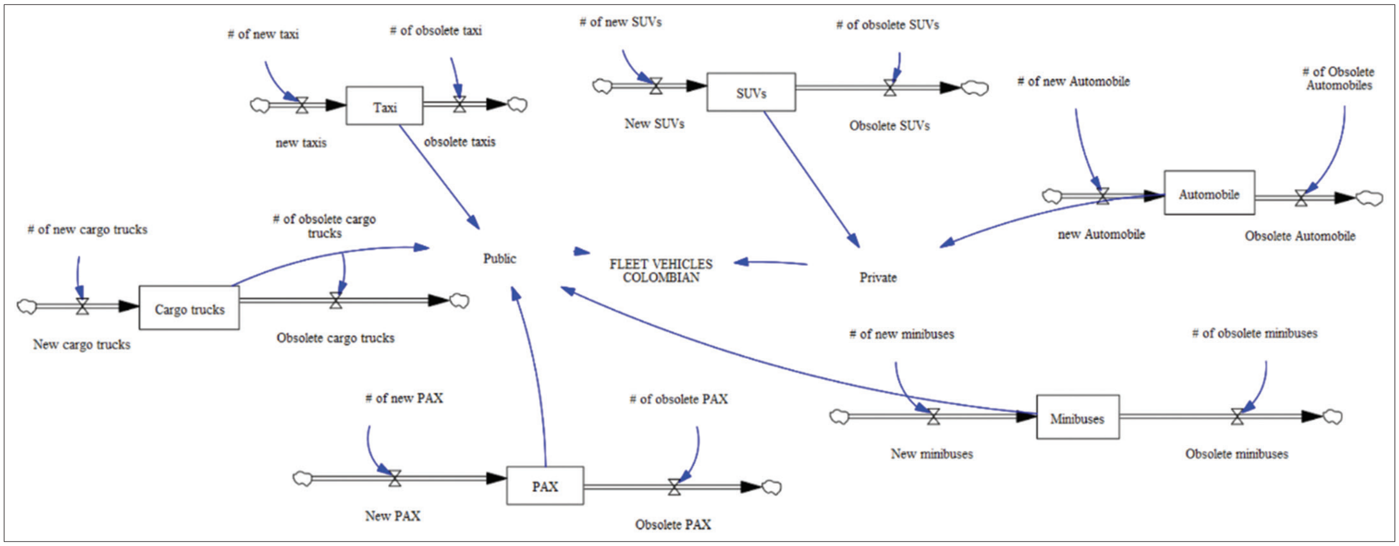


Figure 7: Fuel consumption taxi, automobiles y SUVs

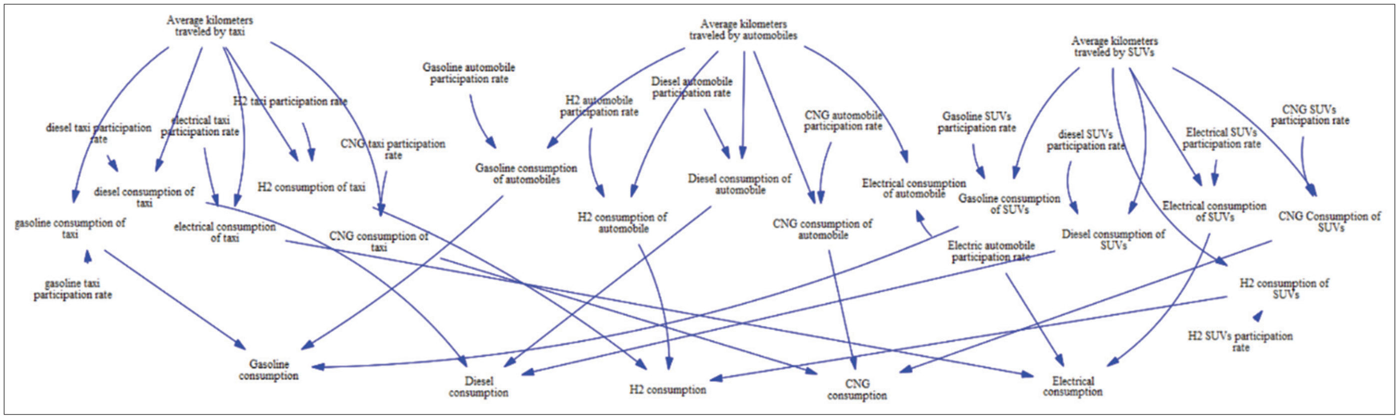
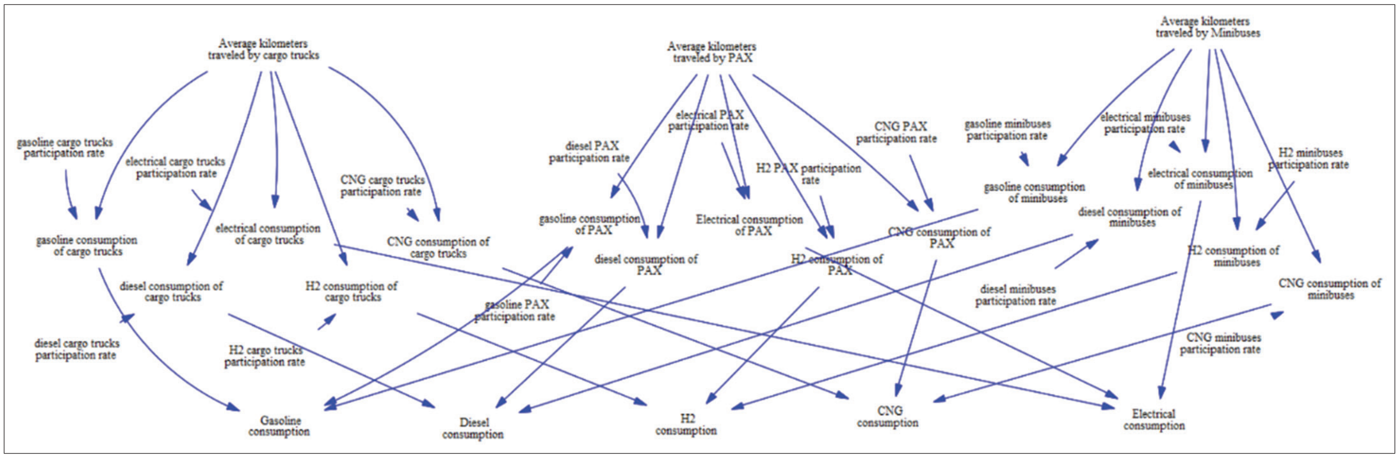


Figure 8: Fuel consumption Cargo trucks, PAX y minibuses



2.5.1. Model validation

After quantifying the model, the model structure was verified to check the consistency of the units used for each variable. Additionally, the data used in the model was obtained from official government sources related to the transportation and energy sectors (sources in Table 4), indicating that the data is reliable.

In addition, test runs were carried out within the model, drastically varying the flow and auxiliary variables, observing that the behavior corresponds to the system and that no inconsistencies are generated within it.

Additionally, the selection of the forecast method was made considering the Mean Square Error, for the projection of demand

Figure 9: Emissions by fuel

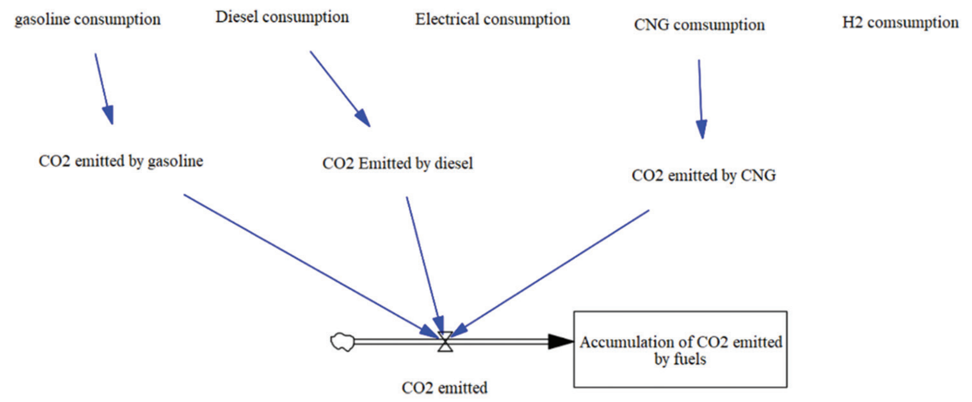
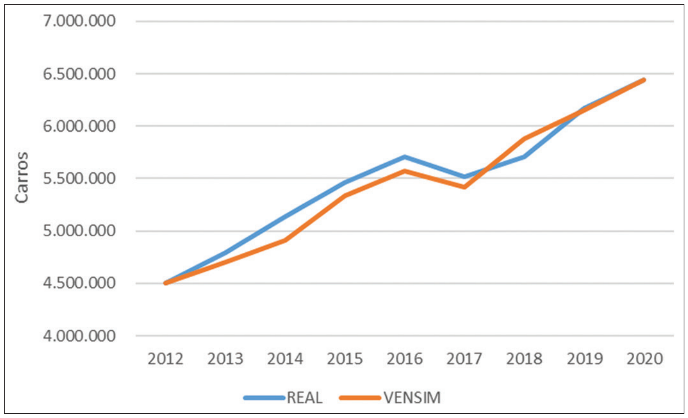


Figure 10: Historical data of vehicle fleet versus projected data on Vensim



until the year 2050, comparing the projections based on the techniques: moving average, simple exponential smoothing, double exponential smoothing, and the "tool" forecast" from Excel. The latter was found to have a lower root mean square error and was therefore selected for this projection.

Finally, in the validation process, historical data is used and compared with available and/or projected data, and coherence is found between the data, as shown in Figure 10.

3. RESULTS AND DISCUSSION

After validating the model, the different scenarios are analyzed, where the gradual inclusion of hydrogen-powered vehicles is considered based on Colombia's hydrogen roadmap, thus visualizing the behavior of the environmental effects and the implications of the zero vehicle emissions.

For the construction of these scenarios, *the 1964 Law of 2019 was considered, which states that cities must progressively replace vehicles purchased for public transportation with zero-emission vehicles in the following years* (Ministerio de Minas y Energía República de Colombia, 2019).

Table 2: Level variable

Level variable	Unit	Equation
Automobile	Und	New Automobile (Und)-Obsolete Automobile' (Und)
SUVs	Und	New SUVs (Und)-Obsolete SUVs (Und)
Cargo trucks	Und	New cargo trucks (Und)-Obsolete cargo trucks (Und)
Minibuses	Und	New minibuses (Und)-Obsolete minibuses (Und)
PAX	Und	New PAX (Und)-Obsolete PAX (Und)
Taxi	Und	New taxi (Und)-Obsolete taxi (Und)
Accumulation of CO_2 emitted by fuels	Kg	CO_2 Emitted (kg)

Table 3: Flow variable

Flow variable	Unit	Equation
New automobile	Und	# of new automobile (Und)
Obsolete automobile	Und	# of obsolete automobile (Und)
New SUVs	Und	# of new SUVs (Und)
Obsolete SUVs	Und	# of obsolete SUVs (Und)
Obsolete Cargo trucks	Und	# of obsolete cargo truck (Und)
New cargo truck	Und	# of new cargo trucks (Und)
CO_2 emitted	kg	CO_2 Diesel (kg)+ CO_2 Gasoline (kg)+ CO_2 CNG (kg)=Kg
New minibuses	Und	# of new minibuses (Und)
Obsolete minibuses	Und	# of obsolete minibuses (Und)
New PAX	Und	# of new PAX (Und)
Obsolete	Und	# of obsolete PAX (Und)
New taxi	Und	# of new taxi (Und)
Obsolete taxi	Und	# of obsolete taxi (Und)

The scenarios are analyzed, including hydrogen-powered vehicles, considering the country's established hydrogen roadmap. This allows for the visualization of the environmental effects and implications of using zero-emission vehicles, as shown in Table 5.

3.1. Scenarios

The considerations considered for each scenario are described.

Base Scenario: In this scenario, the maximum useful life of public transportation vehicles is set to 30 years, as stipulated in Law 105 of 1993. This assumption is also applied to private vehicles since no law determines the maximum number of years a private vehicle can be in circulation. Additionally, in this

Table 4: Auxiliar variable (Datas)

Auxiliara variable	Unit	Data	References
# of new automobile	Und	:= get data xls	(MinTransporte, 2020)
# of new cargo trucks	Und	:= get data xls	(MinTransporte, 2020)
# of new SUVs	Und	:= get data xls	(MinTransporte, 2020)
# of new minibuses	Und	:= get data xls	(MinTransporte, 2020)
# of new PAX	Und	:= get data xls	(MinTransporte, 2020)
# of new taxi	Und	:= get data xls	(MinTransporte, 2020)
Average kilometers traveled by taxi	km	72.910	(ANDI, 2019)
Average kilometers traveled by automobile	km	15.000	(Renault, 2021)
Average kilometers traveled by PAX	km	95.000	(Alcaldía de Cali, 2017)
Average kilometers traveled by cargo trucks	km	75.000	(Baraya, 2018)
Average kilometers traveled by minibuses	km	72.910	(ANDI, 2019)
Average kilometers traveled by SUVs	km	15.000	(Renault, 2021)
# of obsolete automobile	Und	:= get data xls	(MinTransporte, 2020)
# of obsolete cargo trucks	Und	:= get data xls	(MinTransporte, 2020)
# of obsolete SUVs	Und	:= get data xls	(MinTransporte, 2020)
# of obsolete minibuses	Und	:= get data xls	(MinTransporte, 2020)
# of obsolete PAX	Und	:= get data xls	(MinTransporte, 2020)
# of obsolete taxi	Und	:= get data xls	(MinTransporte, 2020)
Gasoline participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
CNG automobile participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
Diesel automobile participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
Electrical automobile participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
H_2 automobile participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
Gasolina taxi participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
CNG taxi participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
Diesel taxi participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
Electrical taxi participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
H_2 taxi participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
Gasoline SUVs participation rate	%	:= get data xls	(MinTransporte, 2015), (UPME et al. 2019)
CNG SUVs participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Diesel SUVs participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Electrical SUVs participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
H_2 SUVs participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Gasoline Cargo trucks participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
CNG cargo trucks participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Diesel cargo trucks participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Electrical cargo trucks participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
H_2 cargo trucks participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Gasolina PAX participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
CNG PAX participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Diesel PAX participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Electrical PAX participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
H_2 PAX participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Gasoline minibuses participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
CNG minibuses participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Diesel minibuses participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
Electrical minibuses participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)
H_2 minibuses participation rate	%	:= get data xls	(MinTransporte, 2015), (Renault, 2021)

scenario, the participation of each type of vehicle by fuel type is maintained, meaning the inclusion of H_2-powered vehicles is not considered.

P-H Scenario (Public transportation with conditions stipulated in the Hydrogen roadmap): In this scenario, the obsolescence of all vehicles is reduced by 10 years, since a faster rotation of vehicles is required for greater energy diversification within the automotive fleet (UPME, 2020). Similarly, the progressive participation of zero-emission vehicles in the entire public sector is applied according to the Hydrogen roadmap and Law 1964 of 2019.

Figure 11: H_2 Consumption by scenarios in kT

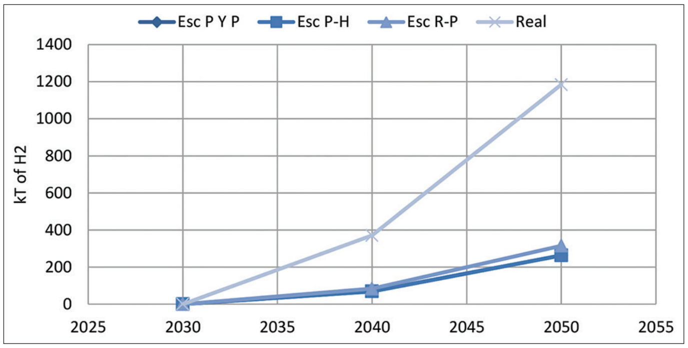


Figure 12: CO_2 emitted into the environment

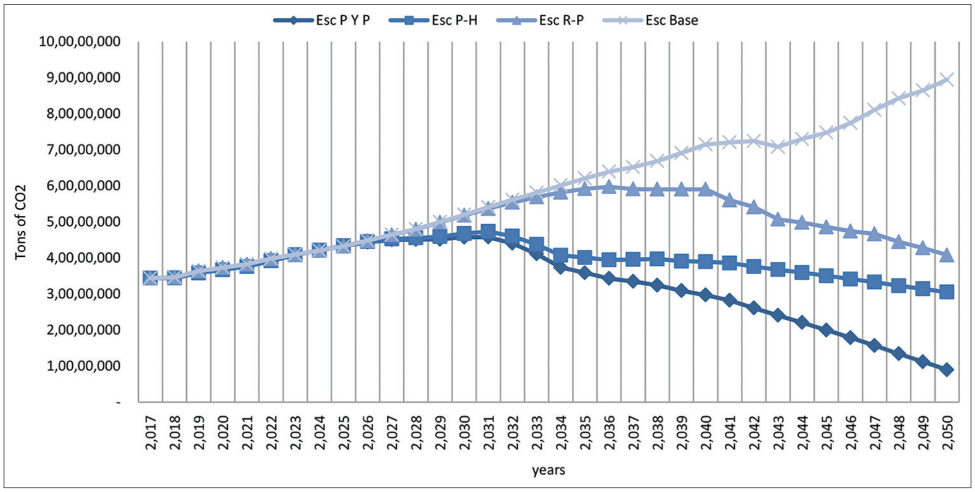


Figure 13: CO_2 accumulation (kT of CO_2)

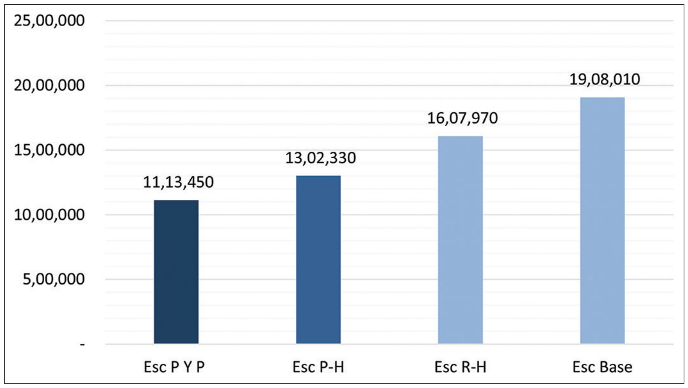


Table 5: 1964 Law of 2019

Years	Percentage of vehicles purchased
2025	10
2027	20
2029	40
2031	60
2033	80
2035	100

Source: Own elaboration with data from the Ministry of Mines and Energy.

Table 6: H_2 consumption in kT H_2

Scenarios	2030	2.040	2.050
P and P Scenario	0,45	69,016	263,383
P-H Scenario	0,45	69,016	263,383
R-P Scenario	0,45	83,559	315,351
Base Scenario	-	-	-

Source: Own elaboration

R-P Scenario (Delay in the implementation of Law 1964 of 2019): In the R-P scenario, Law 105 of 1993, which considers a useful life of 30 years for vehicles, is considered. It is important to consider that 41% of public works in Colombia are delayed (Ministerio de Transporte de Colombia, 2019). Therefore, this scenario proposes a delay of 5 years in the implementation of the law due to infrastructure. Thus, implementation begins in 2030 instead of 2025, and the Hydrogen roadmap is fully implemented in this scenario.

P and P Scenario (Replacement within public and private transportation): In this scenario, the years of obsolescence are reduced to 20 years, with the same assumption that the automotive fleet requires a faster rotation of vehicles. It also considers the implementation of Law 1964 of 2019 for vehicles in the public sector and extends it to the private sector. Additionally, the Hydrogen roadmap is applied.

3.2. Analysis of the Results

3.2.1. Hydrogen consumption in kilotons (kT)

Figure 11 and Table 6 show the H_2 consumption that the vehicle fleet would have in the 3 scenarios. This consumption is within the limits of the hydrogen roadmap, which for the years 2030, 2040, and 2050 allocates 0.4 kT, 371 kT, and 1184 kT respectively for the transportation sector. That said, any of the 3 scenarios could be applied to Colombia without a supply problem. It should be noted that for the years 2040 and 2050 the supply of H_2 as fuel to air and maritime transport in Colombia is included, this may be the reason why there is a difference between the consumption of the model and the hydrogen roadmap.

3.2.2. CO_2 emitted into the environment

Figure 12 shows the emissions per year for each of the scenarios, where it can be observed that significant differences between the scenarios begin to appear from 2030 onwards. This is because the law of 1964 began to be applied to a higher percentage of zero-emission vehicles. Furthermore, at the end of the simulation in 2050, there is a percentage difference between the P and P scenarios of 90%, 65.5% for P-H, and 54.4% for R-P compared to the base scenario.

3.2.3. CO_2 accumulation

When CO_2 is released into the environment, it can take billions of years to disappear from the atmosphere (Pachauri and Meyer, 2014). For this reason, it is important to observe the accumulated emissions in each of the scenarios.

In Figure 13, the minimum difference between the base scenario and the scenario with the highest CO_2 accumulation is 300 million tons of CO_2, while with the best scenario, which is P and P, the difference in production is 794 million tons of CO_2 compared to the base scenario.

4. CONCLUSION

During the bibliographic review, it was found that the Colombian vehicle fleet is divided into 7 types of vehicles: motorcycles, cars, vans, PAX (buses and minibuses), cargo trucks, minibuses, and taxis, with an average age of 16 years (ANDEMOS, 2017). Furthermore, 82% of the fleet is made up of private cars and the remaining 18% are public vehicles, of which 99% run on fossil fuels (gasoline, diesel, and CNG), each of which generates a different amount of emissions due to the particularities of the country (RUNT, 2020).

In addition, the model developed previously made it possible to observe what could happen within the Colombian automotive fleet in terms of its growth and what the consequences could be if actions are not taken to include zero-emission vehicles, such as hydrogen-powered cars. Thanks to the dynamic simulation, information was obtained about this behavior that can be used for decision-making, representing a good alternative for the inclusion of hydrogen-powered automobiles.

In all the proposed scenarios, a decrease in CO_2 emissions is generated compared to the base scenario, because the scenarios include zero-emission vehicles, whether powered by hydrogen or electric. It should be noted that the scenario with the greatest reduction was the P Y P, thanks to the fact that Law 1964 of 2019 was also applied in the private sector, this being the sector with the greatest participation within the vehicle fleet; Reflecting that, if Colombia wants to reduce CO_2 emissions by 90% in the long term, this scenario would generate an important contribution to said goal, so policies that strengthen and have a greater incentive than the current one for this type must be implemented. of technologies. promoted, especially in the private sector.

Consequently, to support the proposed scenarios, government entities must ensure correct distribution and operating capacity, in addition, sufficient stations to recharge each vehicle, whether powered by H_2 or electricity.

The model allowed us to verify the change in the Colombian vehicle fleet and the effect of vehicle obsolescence, as well as the fuel consumption and CO_2 emissions of each one, in addition to the effects that come with the implementation of clean technologies in improving the environment.

It is recommended that future studies consider including hydrogen-powered motorcycles in the model, as they are still in development. In addition, economic aspects must be included such as fuel prices, maintenance costs, replacement costs of electric vehicles and H_2, vehicle prices, the force that social networks can have in the use of this type of technology, and the location of H_2 refueling points. Be considered. Likewise, the emissions from the manufacturing of each fuel and other types of greenhouse gases emitted by the vehicle fleet, such as CO, particulate matter (PM), and nitrous oxide (N_2O), were not considered in the model due to their low stake, it should be considered.

Although the model has been built according to the characteristics of the vehicle fleet and Colombian regulations, it is a model that can be adjusted to other countries and regions and will allow evaluation of the environmental effects of the transition in transportation vehicles from fossil fuels. to hydrogen.

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