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Evaluating low-carbon policy alternatives to support electric vehicle transition: evidence from Bogota-Colombia

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Abstract: The transition from fuel-based vehicles to electric vehicles (EVs) is fundamental in the decarbonisation process of countries – it has become an option to reduce greenhouse gases (GHG). This transition involves transformations of the transport sector that are influenced by transport policy. However, policy makers sometimes experience delays in implementing such a policy, which produces drawbacks in the long-term. The paper aims to assess low-carbon policy alternatives for mitigating the delays in the electric vehicles transition, supported by a simulation model. To simulate, the model uses the historical data of pollution and temperature generated by the Bogota's transport sector in Colombia. Results contribute to understanding the role of low-carbon policy on the reduction of CO_2 emissions in the transport sector. Also, a dynamic perspective shows how the EVs transition in the case of Colombia influences on the desired target policy, such as the Paris Agreement and the intergovernmental panel on climate change (IPCC).

1 Introduction

Nowadays, the nations have taken action about climate change to reduce its effects [1]. Indeed, several countries have adopted the intergovernmental panel on climate change (IPCC) agreement to reduce the increase of global warming to 1.5 ºC [2] as well as the Paris Agreement to reach global temperature below 2 ºC [3-5]. However, these efforts have not yet been sufficient. Previous studies have agreed that, despite these efforts, policy alternatives are needed to support this issue [6-9]. This is corroborated by the emissions growth in several countries [10-12].

In the metropolitan areas of developing countries, the emissions impact is much more significant because of the speed of urbanisation [13]. The urbanisation brings new challenges in terms of transportation and emission reduction, which involve improving the transport policy. For instance, both Mexico and Brazil are among the top 20 emitters with 1.33% of global emissions each, despite adopted transport policy to expand clean transport systems in the last years [14]. In the case of Colombia, the contamination caused by the transport system has not been an essential point on the agenda of policymakers. This situation has brought an increase in the generation of emissions from the transport sector [8,9,15].

Despite Colombia has promoted Sustainable Development Goals – SDGs for protecting the environment, emissions from transportation are still expected to rise in the future [16]. The transport sector has seen a rise in emissions over the last decade. In 2006, 16.2% of all CO_2 emissions were from solid fuel consumption in Colombia and by 2016, its contribution to CO_2 emissions had grown to 23.2% [17], where transport represented 13.5% of this increase [8]. Although electric and hybrid vehicles are less contaminant than gasoline and diesel engines, the diffusion of clean technologies for the transport sector in Colombia has been insufficient.

In this context, this paper assesses the following questions through a simulation model: i) Is it possible to mitigate the CO_2 emission levels with electric vehicle diffusion in Bogota, Colombia until 2050? ii) Could low carbon policies (i.e., Paris agreement or IPCC) foster electric vehicles transition for 2050 in the case of Bogota, Colombia? and iii) What are the impacts of transition delays of electric vehicles on both emissions and temperature in Bogota's transport sector in Colombia?

A low carbon policy for transport system involves identifying the relationship between different categories of transport and their generated emissions [6,18]. Moreover, the policy issue at the regional and national level comprises delays and feedbacks, which could affect the transition processes. Thus, this paper developed a simulation model for understanding dynamics behaviour of the transport system, including different types of technology (e.g. fuel, hybrid, electric vehicle) and the effects of delays in technology transition on the generation of emissions, particularly for electric vehicles.

Several well-known simulation approaches have been used for evaluating transport policy and electric vehicle technology [19,20]. In this sense, system dynamics methodology has offered an excellent fit to evaluate the transition of the electric vehicle [6,8,19,21,22]. The system dynamics modelling comprises nonlinear dynamics, delays and feedback loops, which are simulated over time [23-25]. Although previous research has used the simulation to analyse causality between low carbon policy and electric vehicle transition [6-8,26,27], there are few studies that address the effects of delay on vehicle technology transition, assessing the low carbon policy targets, especially in the case of Colombia. Thus, a model based on system dynamics simulation was developed to understand the incidence of transition on emissions and temperature.

This paper is structured as follows: Section 2 describes the main background of the research. Section 3 explains the simulation model used for assessing the low carbon policy in Bogota's transport sector in Colombia. Results obtained from the simulation model are presented in Section 4. Finally, the conclusions are presented in Section 5.

2 Background of the research

Due to the increase from 3.4 million vehicles in 2018, mainly determined by private transport demand, the transport sector has become an essential contributor to CO2 emissions in Colombia [10,28]. This situation has provoked resources depletion with a negative impact on the environment as well as public health impacts. Currently, private vehicles produce high emissions at the local level, particularly in Bogotá and Medellin, which has forced the public intervention of policymakers to reduce CO2 emissions [8,16]. A fuel vehicle can emit 256 grams of CO2 per kilometre travelled, while hybrid vehicles generate 85 grams, that is 67% less; as for a hybrid electric plug-in vehicle, it emits 43 grams, 83% less; and an electric vehicle, zero-emissions [29].

The electric vehicles have a significant impact on the process of decarburisation of the environment [11,30]. However, the electric vehicles transition for passengers' transportation requires the construction of new infrastructure [31-33]. Inside the process of transition from fuel vehicles to electric vehicles, there is evidence of the increase of innovation processes [34]. Proof of this is that some countries such as Germany, Sweden, Brazil and China have incorporated scheme for development of electric vehicles industry, generating innovation and changes on conventional energy systems [32,35,36].

Over recent years, several strategies have been developed to support electric vehicle transition [6,37-39]. The research on electric vehicles transitions have been addressed from different aspects. First, studies that associate passenger flows to determine transport capacity and demand [40-42]. Second, studies that assess the electric vehicles diffusion and its impact on the environment [11]. Third, studies related to analyse the transport congestion [43]. This paper contributes to analysing the delays of the electric vehicle transition in the case of Bogota city and their effects on the policy targets of emissions reduction.

The transition of the fuel vehicle to the electric vehicle could be understood around different modelling approaches [27,44]. In this paper, the system dynamics modelling is proposed to represent the interaction between delays of the electric vehicles transition and its effects on the environment (i.e., CO2 emissions and temperature). System dynamics is an approach based on the feedback control theory used to analyse complex system [6,45-47]. As the transport system involves complex relationships, the traditional approaches (e.g., optimisation approach) are not suitable to understand the delays of the system and their effects in the long term [9,19,48,49]. By utilizing a system dynamics model, a comprehensive system-based view of transport planning can be achieved, and this can be utilized to show decision-makers the importance of these feedbacks and lagged responses [19]. Thus, system dynamics has been applied in this paper. The paper describes the model's dynamics, as well as providing a brief explanation of the mathematical model used.

3 Methodology and model description

A simulation model was built on understanding the dynamics of the delays of electric vehicles transition and their effects on the CO2 emissions and temperature. The proposed model was developed as a stock and flows diagram, including three interconnected sections. In the first section, the model comprises the private and public vehicles according to the different types (i.e. gasoline, diesel, electric vehicle). The second section represents the dynamic of the accumulated emissions generated by fossil fuel vehicles. The third section shows the changes in temperature. Details on the sections of the simulation can be observed in Figure 1.

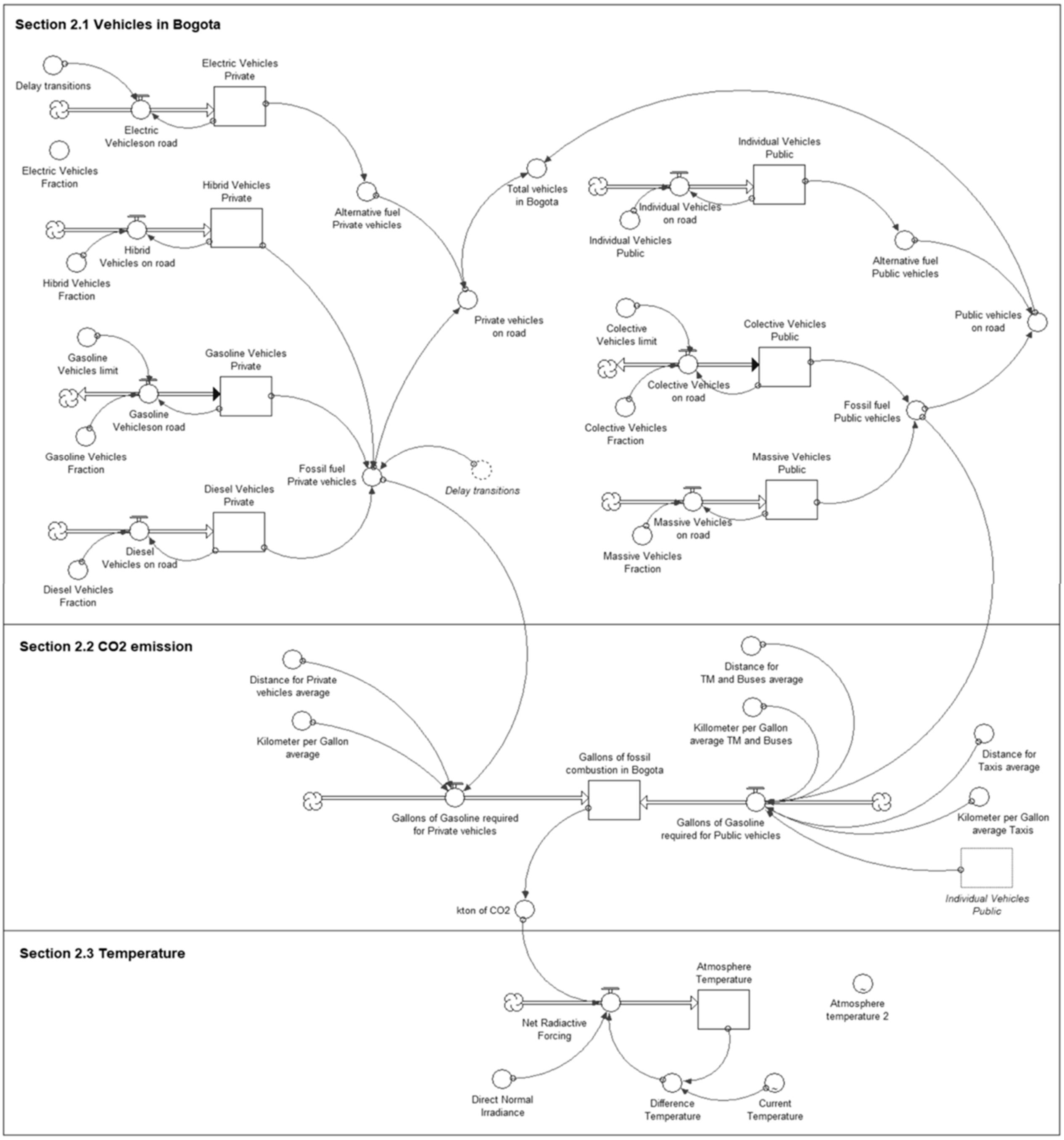

Figure 1 Simulation model for the case of study of Bogota City

The stock-and-flow diagram is composed of a system of differential equations, which is solved through a simulation structure. For instance, in section 2.1 – vehicles in Bogota – the accumulated electric vehicles private (EVp) (1) and electric vehicles on road (evr) (2) was calculated by Equation 1 and 2, respectively. A brief explanation of the model structure is presented below.

$$EVp\ (t) = EVp(t-1) + \int evr(t)\ (dt) \qquad (1)$$

$$evr\ (t) = EVp(t-\varphi) \qquad (2)$$

Where,
φ: is the constant delay time.

3.1 *Total vehicles in Bogota*

The vehicles are classified according to the type of service as private, official, public transportation and diplomatic, as illustrated in Figure 2. Besides, public transportation by type of service can be individual,

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collective and mass transit. The data was taken of the transport secretary of Bogota [50] according to the type of technology (i.e. gasoline, diesel, hybrid and electric vehicles) for private and public transportation.

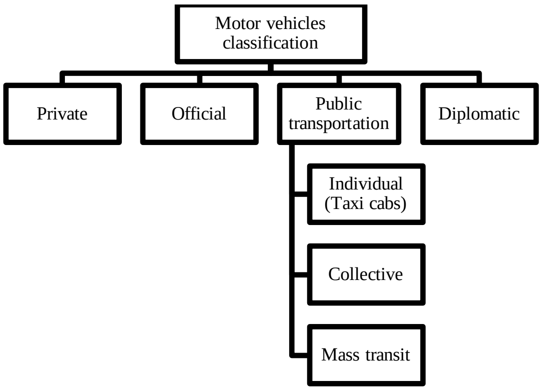

Figure 2 Vehicles classification in the Bogota city
Source: Adapted from Secretaria Distrital de Bogota [50]

3.2 CO_2 emissions

The CO2 emissions are calculated as from the gallon of gasoline and diesel – 8,887 grams CO2 per gallon for gasoline and 10,180 grams of CO2 for diesel [51]. The gallon consumed per fuel vehicles is the average between gallon per kilometre and distance travelled. For private fuel vehicles, it is estimated 40 kilometres per gallon [km/gal] and 30 kilometre per day [km/day] [52]. On the one hand, public fuel vehicles reach an average of 45.8 [km/gal] for taxis [53], while for collective and mass transit is 6.36 [km/gal] [54]. On the other hand, the distance travelled per day of one taxis is 232 [km] [53], and 300 [km] for collective and mass transit [54]. An initial value of CO2 equivalent was taken from ground transportation of 4745 kilotons by 2012 [55].

3.3 Temperature section

This sector was adapted from Fiddaman's model for analysing the temperature, as illustrated in Figure 3 [56]. The variables used to calculate the atmosphere temperature are: i) previous CO2 emission, ii) direct normal irradiance, and iii) the net radiative forcing. The direct normal irradiance – DNI – for Bogota used in the model was 1177 kWh/m2 per year [57]. The net radiative (F) (3) forcing to CO2 is calculated from Equation 3 [58].

$$F = 5.32\, ln\left(\frac{C}{C_o}\right) + 0.39\left[ln\left(\frac{C}{C_o}\right)\right]^2 \qquad (3)$$

Where C represents the concentration of CO_2, while C_0 is equal to 278×10^{-6}.

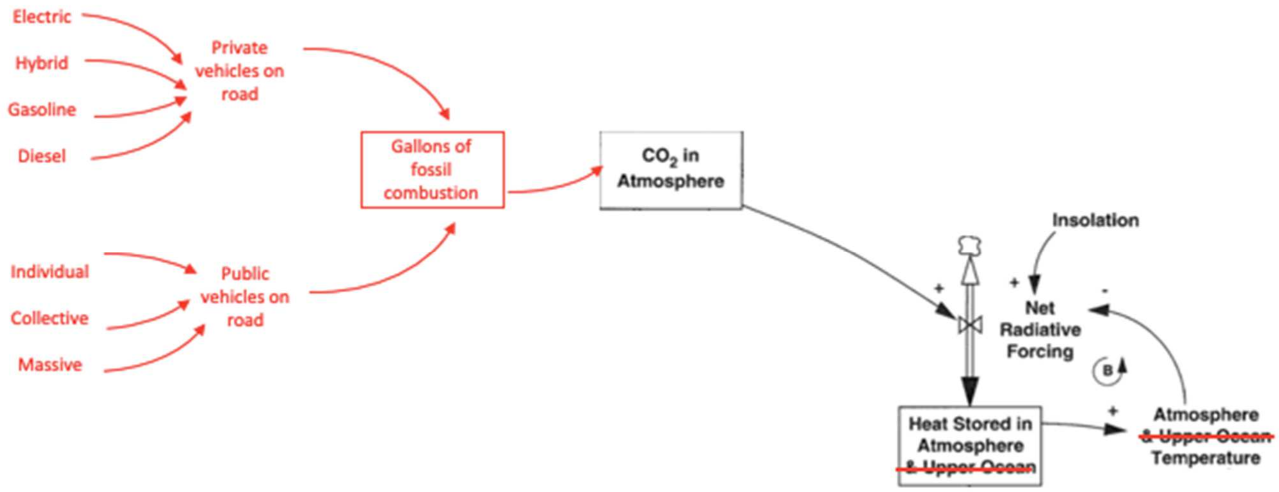

Figure 3 Temperature sector adapted from Fiddeman's model

3.4 Model validation

The simulation model developed was extensively validated. This research applied tests of consistency and dimensionality suggested by [59-61]. Experts confirm the dimensions of the simulation model through checking based on previous studies [6,7,15]. Figure 4 presents a model behaviour test for the actual CO2 emission levels data – reference mode – and simulated data from 2000 to 2017. It can be seen that both levels of CO2 have the same trend (red line). Thus, the simulation model passes the behaviour validation test for carrying out the following scenarios of simulation.

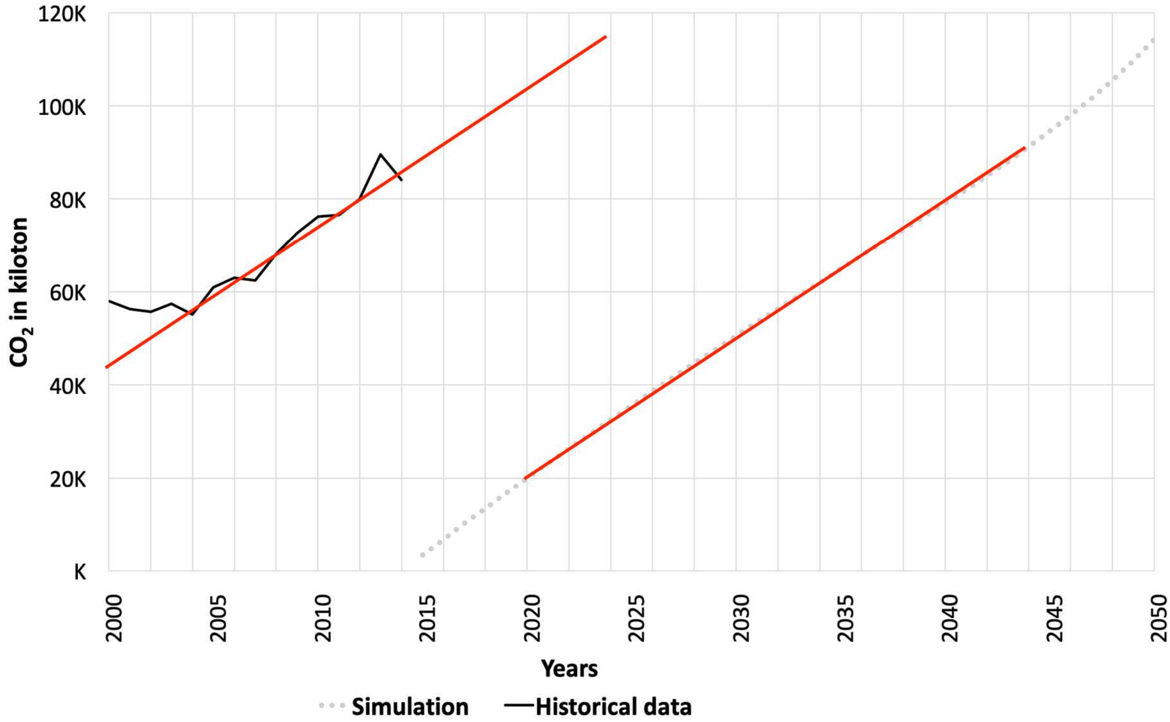

Figure 4 Model behaviour tests for CO_2 emission levels of Bogota

3.5 Simulation scenarios

We simulated the model within four scenarios. These scenarios represent the delays in years of EVs transition in the next years by Bogotá, as shown in Figure 5. The first scenario represents current conditions – business as usual (BAU). There are no incentives or stimulates to gain EVs in this scenario. The acquisition of the EVs continues with a lower increase like up to now. This scenario does not consider any of the environmental agreements such as Paris agreement – limit global warming to 2.0 ºC – or IPCC – limit global warming to 1.5 ºC. The second scenario considers 15 years for electric vehicles transition, namely the incentives for the acquisition of EVs will be after 15 years. Delaying electric vehicles transition could generate uncertainty for infrastructure development in the short term. Insufficient infrastructure for attending new alternatives transportation produces congestion problems. The third scenario considers a delay of 10 years for the transition of clean technology alternatives. This scenario represents a transition not far so long to develop infrastructure and incentives to foster EVs acquisition, searching to align with the global environmental policy, such as Paris agreement and IPCC. The fourth scenario considers encouraging the transition to acquire EVs within the next 5 years. This scenario shows a positive development in infrastructure and tax reduction to the incentive in the acquisition of EVs. The concept to invest in EVs will help to reduce the CO_2 emission levels.

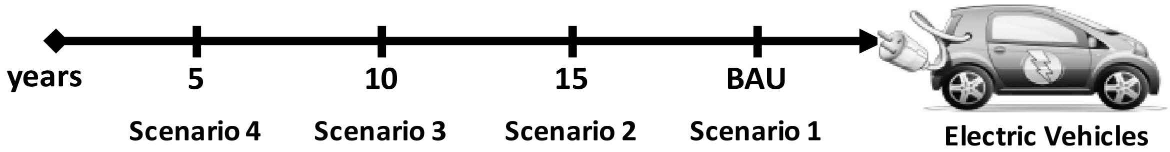

Figure 5 Proposed scenarios to assess the EVs transition

In summary, the scenarios focus on the low carbon policy proposed in Table 1. These policies allow assessing the trend of the temperature and CO2 emission levels between 2018 and 2050 according to the transition to EVs.

Table 1 Low carbon policy proposed

Scenario	Description	Equation within the simulation model	Alternatives of low carbon policy for the EVs transition (φ)
1	Business as usual – BAU		-
2	Uncertainty for infrastructure development		15
3	Searching to align with the worldwide environmental policy	$evr\ (t) = EVp(t-\varphi)$	10
4	Optimistic development in infrastructure and tax reduction to the incentive in the acquisition of EVs		5

4 Results

4.1 Electric vehicle transition

Private EVs have an exponential increase in the four scenarios, as illustrated in Figure 6. Scenarios 2, 3 and 4 show an increase of 1.5 million EVs for every 5 years of transition, while the scenario 1 shows a reduction of 5.5 million EVs for the year 2050 due to the delays for the EVs transition in Bogota. Although these results are similar to the results obtained by Ospina et al. [7] and Herrera et al. [6] in terms of the growth of private electric vehicles in Bogota, our results consider the targets of the environmental policy of the Paris agreements and IPCC. The fragmentation between the design and implementation policy caused by the transition delays produces effects on temperature and emission reduction in the long-term.

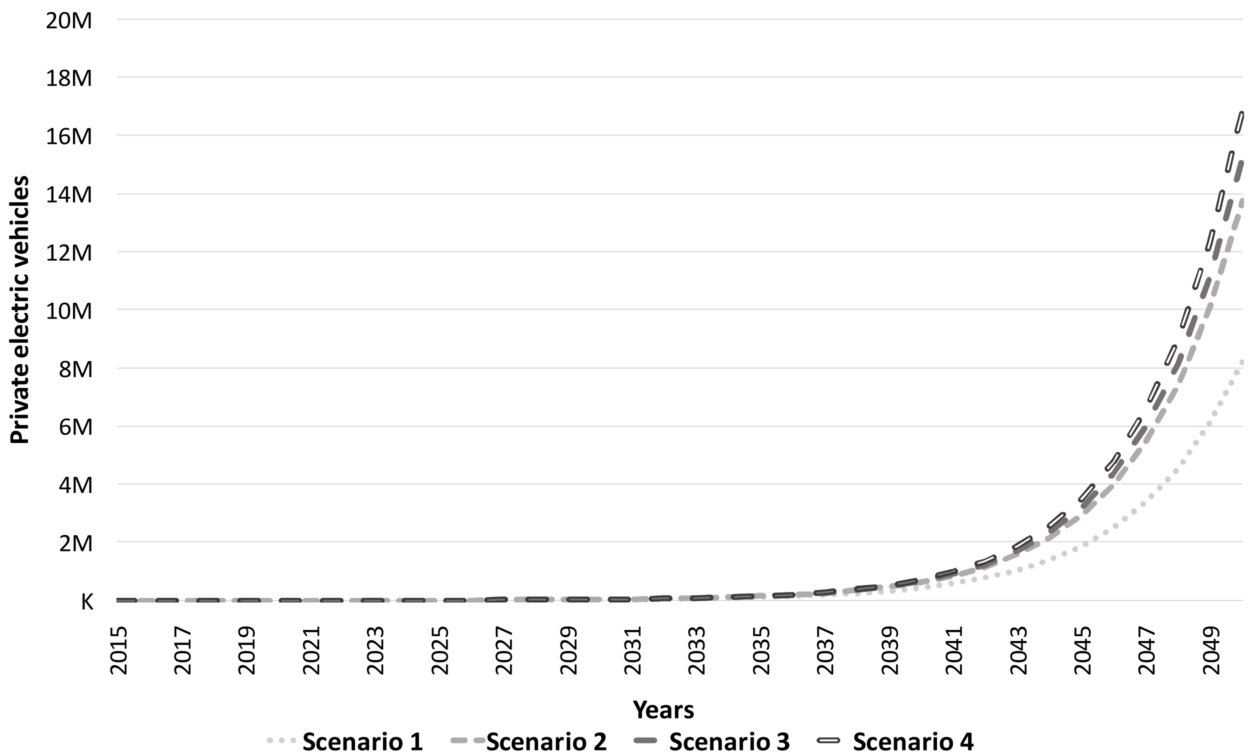

Figure 6 Private electric vehicles trend until 2050 in Bogota

The simulation shows that scenarios 3 and 4 increase amount of EVs compared with BAU scenario by 2050, as presented in Table 2. These results show how an increase in EVs as from investment has a positive impact on transportation, while the lack of EVs diffusion and financial resources could affect the transportation system.

Table 2 Electric vehicles transition by 2050

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EVs for 2050 in million	8.2	13.7	15.2	16.8

4.2 CO_2 emission levels

The trend of CO2 emission levels for the next 30 years is represented in Figure 7. This behaviour is associated with the EVs dissemination in Colombia according to the proposed scenarios (Table 1). The percentage from 2012 to 2050 for the four scenarios are: the first scenario is 24.8%, the second scenario is 9.3%, the third scenario is 6.4%, and the fourth scenario is 3.4%. Results show that the increase in the CO2 emission levels for all scenarios is very high. Scenario 1 represents the highest increase, while scenario 4 represents the lowest increase for the CO2 emission levels. On the one hand, these results disagree with Ospina et al. [7]; however, both studies show the need for an environmental policy for the case of Bogota city. On the other hand, the results under the BAU scenario coincide with the increase between 2030 and 2050 reported by Espinosa et al. [7] BAU scenario by 2050 shows an increase of 24.8% in the CO2 emission levels. This trend is directly associated with the traditional use of fossil fuel in the city [15]. As different delays can occur in Colombia, it may affect the EVs diffusion. Thus, the CO_2 emissions can increase in all scenarios because of a higher dependence on fossil fuel and gas. Other studies also agree a higher dependence on fossil fuel does not allow to reduce the emissions [6,7].

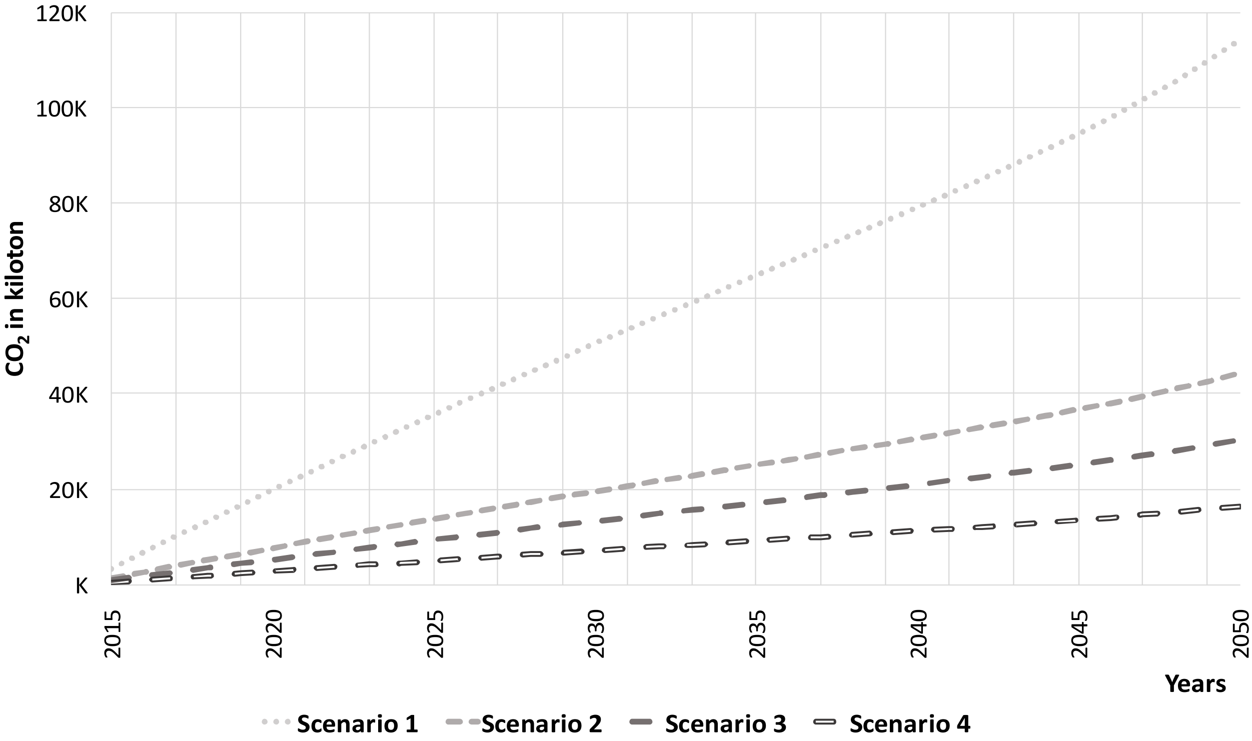

Figure 7 CO2 emission levels trend until 2050 in Bogota

Table 3 shows the CO2 emission levels by 2050 for each of the scenarios. The fourth scenario shows a decrease in CO2 emission levels due to a reduction of fuel vehicles. This situation might achieve with policy alternatives focus to foster clean technologies; however, the complementarity with other policies (e.g., energy policy and transport policy) should be considered.

Table 3 CO2 emission levels by 2050

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CO_2 emission for 2050 in kilotons	114,266	44,392	30,417	16,442

4.3 Temperature variation

An analysis of the behaviour of temperature for future years is presented in Figure 8. Both the CO2 emission levels, and the temperature suffer the highest increase for the next years (see, Figure 7 and 8). The first scenario shows an increase of 2.09 ºC for the temperature more than the fourth scenario that presents the lowest increase for the temperature with an increase of 1.72 ºC.

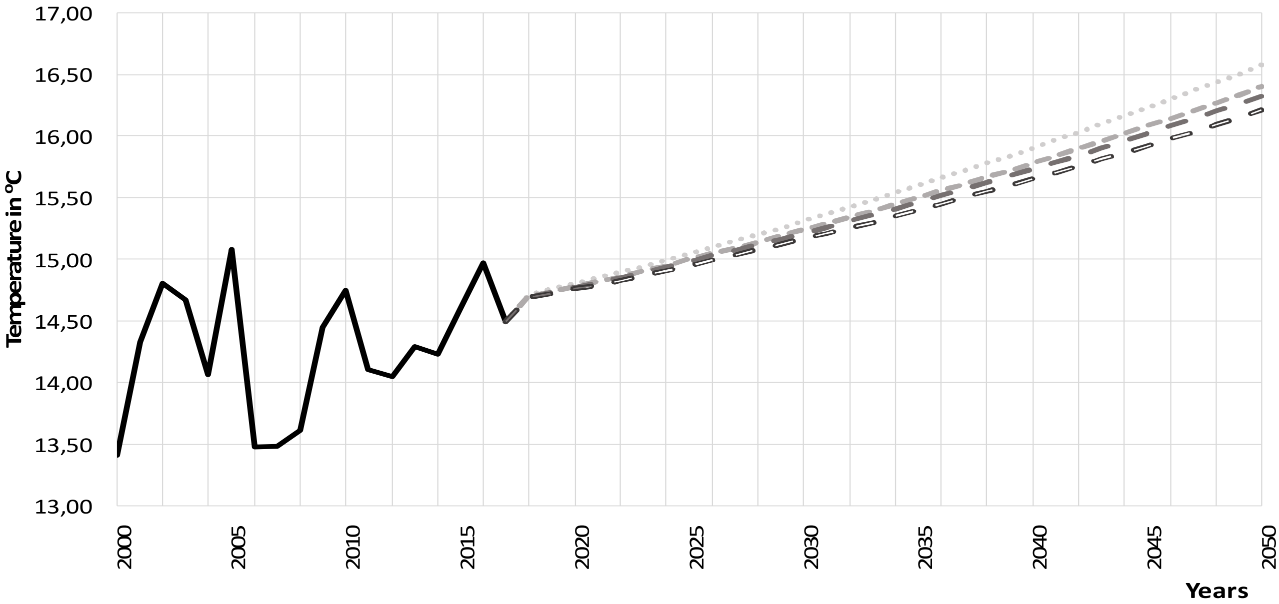

Figure 8 Temperature trend until 2050 in Bogota

Table 4 presents the temperature for each of the proposed scenarios by 2050. For achieve the reduction of the temperature through electric vehicles transition, it is necessary to foster a positive interaction between private industry and government.

Table 4 Temperature variation by 2050

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Temperature by 2050 (C°)	16.58	16.40	16.32	16.21

Although the scenarios do reduce emissions, the results show that it is insufficient in comparison with the goal of the Paris Agreement and IPCC, as illustrated in Figure 9.

The difference in temperature for the four scenarios in comparison to the temperature mean for Bogotá are: the first scenario is 2.09 ºC, the second scenario is 1.91 ºC, the third scenario is 1.83 ºC, and the fourth scenario is 1.72 ºC.

Results show that none of the four scenarios meets the IPCC criteria to limit the increase of 1.5 ºC global warming. The fourth scenario exceeds the IPCC criteria in 0.22 ºC; however, scenario 4 has less difference value in comparison to the other scenarios. The first scenario exceeds 0.59 ºC, the second scenario exceeds 0.41 ºC, and the third scenario exceeds 0.33 ºC. The Paris agreement criteria limit the increase to 2 ºC above the actual mean temperature is fitted by the scenarios 2, 3 and 4. The first scenario shows that it exceeds 0.09 ºC.

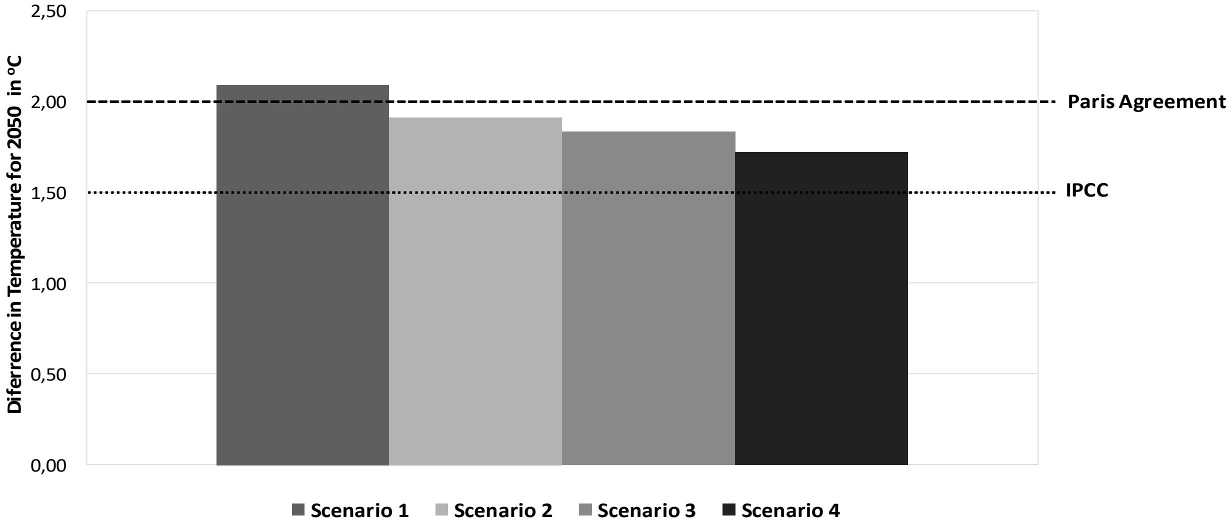

Figure 9 Difference in temperature by 2050

5 Conclusion

This paper has explored scenarios for the electric vehicle transition in the case of Bogotá, Colombia. Results show several lessons for understanding the long-term effects of delays in EVs diffusion for developing countries.

First, it is not sufficient to incentive the acquisition of EVs to reduce the CO2 emission levels. Similar to that reported for other countries [6,62], the subsidies are only beneficial in the earlier year of market introduction and should cover the infrastructure for these clean technologies [6,63,64]. Also, the GHG mitigation in the case of study addressed should include the reorganisation of the transport system: programs to retire old vehicles, better use of the capacity both vehicles and bicycle and intermodal options [10,16,31,65]. Thus, it is urgent to take action to reduce gasoline and diesel engines on private and public vehicles sector.

Second, the results suggest a strong challenge for the mitigation of an environmental issue that allows reaching the targets of the Paris Agreement and IPCC in terms of the EVs transition. Although Bogotá's efforts concerning the accessibility of transportation programs have been the highlight [66], the low carbon policy and its effects in the long-term has not sufficiently discussed.

Third, the paper reflects on the environmental concerns related to the transport system, described as the delays in the EVs transition that affect the targets of the Paris Agreement and the IPCC. In this regard, the paper proposes an intervention systemic for the design of low carbon policy in the case of Bogotá and other developing countries of Latin America.

Although the incentives for the EVs transition are one of the most crucial issues to the diffusion of the clean technology [21,27,67], this paper contributes to assessing the delays as an essential aspect within transport policy design. Considering the delays in the EVs transition could mitigate problems of fragmentation between the design policy and implementation.

The case of Bogota shows that the delayed diffusion of the EVs could affect the targets of the Paris Agreement and IPCC. In this regard, the paper proposes the development in infrastructure and tax reduction to the incentive in the acquisition of EVs over the following five years.

The results suggest prosperous areas for empirical work, which include the modelling – for instance, the analysis of the installed capacity of energy for attending the EVs transition in the case of other cities in Latin America.

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References

[1] NYAMBUU, U., SEMMLER, W.: Climate Change and the Transition to a Low Carbon Economy – Carbon Targets and the Carbon Budget, *Economic Modelling*, Vol. 84, pp. 367-376, 2020. https://doi.org/10.1016/j.econmod.2019.04.026

[2] UNITED NATION: Goal 13: Take urgent action to combat climate change and its impacts, New York, 2019, [Online], Available: https://www.coe.int/en/web/congress/goal-13 [10 Feb 2023], 2019.

[3] MEINSHAUSEN, M., MEINSHAUSEN, N., HARE, W., RAPER, S.C.B., FRIELER, K., KNUTTI, R., FRAME, D.J., ALLEN, M.R.: Greenhouse-gas emission targets for limiting global warming to 2 ºC, *Nature*, Vol. 458, No. 7242, pp. 1158-1162, 2009. https://doi.org/10.1038/nature08017

[4] ROWLANDS, D.J., FRAME, D.J., AINA, T., BOOTH, B.B., CHRISTENSEN, C., COLLINS, M., FAULL, N., FOREST, C.E., GRANDEY, B.S., GRYSPEERDT, E., HIGHWOOD, E.J., INGRAM, W.J., KNIGHT, S., LOPEZ, A., MASSEY, N., MCNAMARA, F., MEINSHAUSEN, N., PIANI, C., ROSIER, S.M., SANDERSON, B.M., SMITH, L.A., STONE, D.A., THURSTON, M., YAMASAKI, K. YAMASAKI, K., ALLEN, M.R.: Broad range of 2050 warming from an observationally constrained large climate model ensemble, *Nature Geoscience*, Vol. 5, pp. 256-260, 2012. https://doi.org/10.1038/ngeo1430

[5] SCHLEUSSNER, C., ROGELJ, J., SCHAEFFER, M., LISSNER, T., LICKER, R., FISCHER, E.M., KNUTTI, R., LEVERMANN, A., FRIELER, K., HARE, W.: Science and policy characteristics of the Paris Agreement temperature goal, *Nature Climate Change*, Vol. 6, pp. 827-835, 2016. https://doi.org/10.1038/nclimate3096

[6] HERRERA, M.M., ROSERO GARCIA, J., CASAS, O.: Systemic analysis of the adoption of electric vehicle technologies in Colombia, *International Review Mechanical Engineering*, Vol. 11, No. 4, pp. 256-269, 2017. https://doi.org/10.15866/ireme.v11i4.11493

[7] OSPINA, D., ZAPATA, S., CASTAÑEDA, M., DYNER, I., ARISTIZÁBAL, A.J., ESCALANTE, N.: Model for evaluating CO2 emissions and the projection of the transport sector, *International Journal of Electrical and Computer Engineering*, Vol. 8, No. 3, pp. 1781-1787, 2018. http://doi.org/10.11591/ijece.v8i3.pp1781-1787

[8] MARTÍNEZ-JARAMILLO, J.E., ARANGO-ARAMBURO, S., ÁLVAREZ-URIBE, K.C., JARAMILLO-ÁLVAREZ, P.: Assessing the impacts of transport policies through energy system simulation: The case of the Medellin Metropolitan Area, Colombia, *Energy Policy*, Vol. 101, 2016, pp. 101-108, 2017. https://doi.org/10.1016/j.enpol.2016.11.026

[9] CALDERON-TELLEZ, J., HERRERA, M.M.: Appraising the impact of air transport on the environment:Lessons from the COVID-19 pandemic,

Transportation Research Interdisciplinary Perspectives, Vol. 10, No. March, p. 100351, 2021. https://doi.org/10.1016/j.trip.2021.100351

[10] ESPINOSA, M., CADENA, A.I., BEHRENTZ, E.: Challenges in greenhouse gas mitigation in developing countries: A case study of the Colombian transport sector, *Energy Policy*, Vol. 124, No. August 2018, pp. 111-122, 2019. https://doi.org/10.1016/j.enpol.2018.09.039

[11] LINDLY, J.K., HASKEW, T.A.: Impact of electric vehicles on electric power generation and global environmental change, *Advances Environmental Research*, Vol. 6, No. 3, pp. 291-302, 2002. https://doi.org/10.1016/S1093-0191(01)00060-0

[12] CHENG, Y.H., CHANG, Y.H., LU, I.J.: Urban transportation energy and carbon dioxide emission reduction strategies, *Applied Energy*, Vol. 157, pp. 953-973, 2015. https://doi.org/10.1016/j.apenergy.2015.01.126

[13] VAFA-ARANI, H., JAHANI, S., DASHTI, H., HEYDARI, J., MOAZEN, S.: A system dynamics modeling for urban air pollution: A case study of Tehran, Iran, *Transportation Research Part D: Transport and Environment*, Vol. 31, pp. 21-36, 2014. https://doi.org/10.1016/j.trd.2014.05.016

[14] WORLD BANK GROUP: 'CO2 emissions from transport (% of total fuel combustion)', [Online], Available: https://data.worldbank.org/indicator/EN. CO2.TRAN.ZS [3 Feb 2023], 2014.

[15] PARDO, C.I.: Energy and sustainable development in cities : A case study of Bogotá, *Energy*, Vol. 92, pp. 612-621, 2015. https://doi.org/10.1016/j.energy.2015.02.003

[16] MUÑOZ-VILLAMIZAR, A., MONTOYA-TORRES, J.R., FAULIN, J.: Impact of the use of electric vehicles in collaborative urban transport networks: A case study, *Transportation Research Part D: Transport and Environmental*, Vol. 50, pp. 40-54, 2017. https://doi.org/10.1016/j.trd.2016.10.018

[17] WORLD BANK GROUP: 'CO2 emissions from solid fuel consumption (% of total) - Colombia', [Online], Available: https://data.worldbank.org/indicator/EN.ATM.CO2E.SF.ZS?end=2019&locations=CO&most_recent_year_desc=false&start=1990&view=chart [3 Feb 2023], 2023.

[18] SHAFIEI, E., DAVIDSDOTTIR, B., LEAVER, J., STEFANSSON, H., ASGEIRSSON, E.I.: Simulation of Alternative Fuel Markets using Integrated System Dynamics Model of Energy System, *Procedia Computer Science*, Vol. 51, pp. 513-521, 2015. https://doi.org/10.1016/j.procs.2015.05.277

[19] SHEPHERD, S.P.: A review of system dynamics models applied in transportation, *Transportmetrica B: Transport Dynamics*, Vol. 2, No. 2, pp. 83-105, 2014. https://doi.org/10.1080/21680566.2014.916236

[20] AL-ALAWI, B.M., BRADLEY, T.H.: Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies, *Renewable and Sustainable Energy Reviews*, Vol. 21, pp. 190-203, 2013. https://doi.org/10.1016/j.rser.2012.12.048

[21] BENVENUTTI, L.M.M., RIBEIRO, A.B., URIONA, M.: Long term diffusion dynamics of alternative fuel vehicles in Brazil, *Journal of Cleaner Production*, Vol. 164, pp. 1571-1585, 2017. https://doi.org/10.1016/j.jclepro.2017.07.051

[22] PFAFFENBICHLER, P., EMBERGER, G., SHEPHERD, S.: A system dynamics approach to land use transport interation modelling: the strategic model MARS and its application, *System Dynamics Review*, Vol. 26, No. 3, pp. 262-282, 2010. https://doi.org/10.1002/sdr.451

[23] BALA, B.K., ARSHAD, F.M., NOH, K.M.: *System Dynamics: Modelling and Simulation*, 1st ed., Springer, Singapore, 2017.

[24] MOLLONA, E.: J. Morecroft, Strategic Modelling and Business Dynamics, A Feedback Systems Approach, *Journal of Management and Governance*, No. 12, pp. 213-217, 2008. https://doi.org/10.1007/s10997-008-9050-0

[25] RAHMANDAD, H., REPENNING, N., STERMAN, J.: Effects of feedback delays on learning, *System Dynamics Review*, Vol. 25, No. 4, pp. 309-338, 2009. https://doi.org/10.1002/sdr.427

[26] BARISA, A., ROMAGNOLI, F., BLUMBERGA A., BLUMBERGA, D.: Future biodiesel policy designs and consumption patterns in Latvia: a system dynamics model, *Journal of Cleaner Production*, Vol. 88, pp. 71-82, 2014. https://doi.org/10.1016/j.jclepro.2014.05.067

[27] STRUBEN, J., STERMAN, J.D.: Transition challenges for alternative fuel vehicle and transportation systems, *Environment and Planning B: Planning and Design*, Vol. 35, No. 6, pp. 1070-1097, 2008. https://doi.org/10.1068/b33022t

[28] BBVA Research: Situación automotriz 2018 Colombia, [Online], Available: https://www.bbvaresearch.com/wp-content/uploads/2018/03/SituacionAutomotriz2018.pdf [4 Jan 2022], 2018.

[29] IEA: Global EV Outlook 2019, [Online], Available: https://www.iea.org/reports/global-ev-outlook-2019 [24 Jan 2022], 2019.

[30] ERCAN, T., ONAT, N.C., TATARI, O.: Investigating carbon footprint reduction potential of public transportation in United States: A system dynamics approach, *Journal of Cleaner Production*, Vol. 133, pp. 1260-1276, 2016. https://doi.org/10.1016/j.jclepro.2016.06.051

[31] ORJUELA, J., HERRERA, M.M., CASILIMAS, W.: *Impact analysis of transport capacity and food safety in Bogota*, Workshop on Engineering Applications-

International Congress on Engineering (WEA), 28-30 October, Bogota, pp. 7-13, 2015.
[32] HAN, J., HAYASHI, Y.: A system dynamics model of CO2 mitigation in China's inter-city passenger transport, *Transportation Research Part D: Transport and Environment*, Vol. 13, No. 5, pp. 298-305, 2008. https://doi.org/10.1016/j.trd.2008.03.005
[33] WANG, Z., ZHANG, Y., LIAN, L., CHU, C.: Evaluating transportation infrastructure investment on a regional level: a system dynamics simulation, *Simulation*, Vol. 94, No. 10, pp. 943-954, 2018. https://doi.org/10.1177/0037549717746750
[34] LO, C.C., WANG, C.H., HUANG, C.C.: The national innovation system in the Taiwanese photovoltaic industry: A multiple stakeholder perspective, *Technological Forecasting and Social Change*, Vol. 80, No. 5, pp. 893-906, 2013. https://doi.org/10.1016/j.techfore.2012.08.016
[35] VASSILEVA, I., CAMPILLO, J.: Adoption barriers for electric vehicles: Experiences from early adopters in Sweden, *Energy*, Vol. 120, pp. 632-641, 2017. https://doi.org/10.1016/j.energy.2016.11.119
[36] SOARES, B., BORBA, M.C., SZKLO, A., SCHAEFFER, R.: Plug-in hybrid electric vehicles as a way to maximize the integration of variable renewable energy in power systems: The case of wind generation in northeastern Brazil, *Energy*, Vol. 37, No. 1, pp. 469-481, 2012. https://doi.org/10.1016/j.energy.2011.11.008
[37] DUTRA, R.M., SZKLO, A.S.: Incentive policies for promoting wind power production in Brazil: Scenarios for the Alternative Energy Sources Incentive Program (PROINFA) under the New Brazilian electric power sector regulation, *Renewable Energy*, Vol. 33, pp. 65-76, 2008. https://doi.org/10.1016/j.renene.2007.01.013
[38] LÓPEZ, M.A., MARTÍN, S., AGUADO, J.A., DE LA TORRE, S.: V2G strategies for congestion management in microgrids with high penetration of electric vehicles, *Electric Power Systems Research*, Vol. 104, pp. 28-34, 2013. https://doi.org/10.1016/j.epsr.2013.06.005
[39] GARCÍA, I., MIGUEL, L.J.: Is the electric vehicle an attractive option for customers?, *Energies*, Vol. 5, pp. 71-91, 2012. https://doi.org/10.3390/en5010071
[40] LEWE, J.-H., HIVIN, L.F., MAVRIS, D.N.: A multi-paradigm approach to system dynamics modeling of intercity transportation, *Transportation Research Part E: Logistics and Transportation Review*, Vol. 71, pp. 188-202, 2014. https://doi.org/10.1016/j.tre.2014.09.011
[41] PROPFE, B., KREYENBERG, D., WIND, J., SCHMID, S.: Market penetration analysis of electric vehicles in the German passenger car market towards 2030, *International Journal of Hydrogen Energy*, Vol. 38, No. 13, pp. 5201-5208, 2013. https://doi.org/10.1016/j.ijhydene.2013.02.049
[42] LIU, X., MA, S., TIAN, J., JIA, N., LI, G.: A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO2 emissions: A case study of Beijing, *Energy Policy*, Vol. 85, pp. 253-270, 2015. https://doi.org/10.1016/j.enpol.2015.06.007
[43] LIU, S., TRIANTIS, K.P., SARANGI, S.: A framework for evaluating the dynamic impacts of a congestion pricing policy for a transportation socioeconomic system, *Transportation Research Part A: Policy and Practice*, Vol. 44, No. 8, pp. 596-608, 2010. https://doi.org/10.1016/j.tra.2010.04.001
[44] BOLWIG, S., BAZBAUERS, G., KLITKOU, A., LUND, P.D., BLUMBERGA, A., GRAVELSINS, BLUMBERGA, D.: Review of modelling energy transitions pathways with application to energy system flexibility, *Renewable and Sustainable Energy Reviews*, Vol. 101, No. June, pp. 440-452, 2019. https://doi.org/10.1016/j.rser.2018.11.019
[45] STERMAN, J.D.: *Business dynamics: systems thinking and modeling for a complex world*, 1st ed., Prentice Hall, New Jersey, 2000.
[46] GARY, M.S., KUNC, M., MORECROFT, J., SCOTT, F.J.: System dynamics and strategy, *System Dynamics Review*, Vol. 24, No. 4, pp. 407-429, 2008. https://doi.org/10.1002/sdr.402
[47] FORRESTER, J.W.: *Principle of Systems*, Productivity Press, Cambridge, 1968.
[48] HERRERA, M.M., HERNÁNDEZ, A., VELANDIA, C.: Una revisión de las contribuciones de la dinámica de sistemas en la transición de vehículos eléctricos, *Inventum*, Vol. 14, No. 27, pp. 89-102, 2019. https://doi.org/10.26620/uniminuto.inventum.14.27.2019.89-102
[49] BIVONA, E., MONTEMAGGIORE, G.: Understanding short-and long-term implications of "myopic" fllet maintenance policies: a system dynamics application to a city bus company, *System Dynamics Review*, Vol. 26, No. 3, pp. 195-215, 2010. https://doi.org/10.1002/sdr.450
[50] SECRETARIA DISTRITAL DE MOVILIDAD: Movilidad en Cifras 2015, [Online], Available: https://www.movilidadbogota.gov.co/web/SIMUR/ARCHIVOS/Movilidad_Cifras_2015_V4_marzo2017.pdf [5 Feb 2023], 2015.
[51] ENVIROMENTAL PROTECTION AGENCY: Greenhouse Gas Emissions from a Typical Passenger Vehicle, [Online], Available: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle [10 Feb 2022], 2018.
[52] CAMARA DE COMERCIO DE BOGOTA: La apuesta por una movilidad sostenible, [Online], Available: https://www.ccb.org.co/Clusteres/Cluster-de-Energia-Electrica/Noticias/2019/Marzo-2019/La-apuesta-por-una-movilidad-sostenible [3 Feb 2022], 2019.

[53] RODRIGUEZ, A., ACEVEDO, J.: ¡Taxi! El modo olvidado de la movilidad en Bogotá, [Online], Available:https://repositorio.uniandes.edu.co/handle/1992/57141 [2 Feb 2022], 2012.
[54] TRANSMILENIO S.A.: Rendición de cuentas 2017, Bogotá, [Online], Available: https://www.idt.gov.co/es/rendicion-de-cuentas-2017 [3 Feb 2022], 2017.
[55] IDEAM, PNUD, MADS, DNP, CANCILLERÍA: Inventario nacional y departamental de Gases Efecto Invernadero – Colombia, [Online], Available: http://documentacion.ideam.gov.co/openbiblio/bvirtual/023421/cartilla_INGEI.pdf [3 Feb 2022], 2016.
[56] FIDDAMAN, T.S.: *Feedback Complexity in Integrated Climate-Economy Models*, Massachusetts Institute of Technology, 1997.
[57] WORLD BANK GROUP: Global Solar Atlas, [Online], Available: https://globalsolaratlas.info/map?c=11.609193,8.349609,3 [4 Feb 2022], 2019.
[58] BYRNE, B., GOLDBLATT, C.: Radiative forcing at high concentrations of well-mixed greenhouse gases, *Geophysical Research Letters*, Vol. 41, No. 1, pp. 152-160, 2014. https://doi.org/10.1002/2013GL058456
[59] BARLAS, Y.: Formal aspects of model validity and validation in system dynamics, *System Dynamics Review*, Vol. 12, No. 3, pp. 183-210, 1996. https://doi.org/10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO
[60] STERMAN, J.D.: Appropriate summary statistics for evaluating the historical fit of system dynamics models, *Dynamica*, Vol. 10, No. 2. pp. 51-66, 1984. https://systemdynamics.org/wp-content/uploads/assets/dynamica/volume-10/10-2/4.pdf
[61] QUDRAT-ULLAH, H., SEONG, B.S.: How to do structural validity of a system dynamics type simulation model: The case of an energy policy model, *Energy Policy*, Vol. 38, No. 5, pp. 2216-2224, 2010. https://doi.org/10.1016/j.enpol.2009.12.009
[62] HARRISON, G., THIEL, C.: An exploratory policy analysis of electric vehicle sales competition and sensitivity to infrastructure in Europe, *Technological Forecasting and Social Change*, Vol. 114, pp. 165-178, 2017. https://doi.org/10.1016/j.techfore.2016.08.007
[63] LU, C., LIU, H., TAO, J., RONG, K., HSIEH, Y.: A key stakeholder-based fi nancial subsidy stimulation for Chinese EV industrialization : A system dynamics simulation, *Technogical Forecasting and Social Change*, Vol. 118, pp. 1-14, 2017. https://doi.org/10.1016/j.techfore.2017.01.022
[64] YU, J., YANG, P., ZHANG, K., WANG, F., MIAO, L.: Evaluating the Effect of Policies and the Development of Charging Infrastructure on Electric Vehicle Diffusion in China, *Sustainability*, Vol. 10, No. 10, p. 3394, 2018. https://doi.org/10.3390/su10103394
[65] ZHANG, L., ZHAO, Z., XIN, H., CHAI, J., WANG, G.: Charge pricing model for electric vehicle charging infrastructure public-private partnership projects in China : A system dynamics analysis, *Journal of Cleaner Production*, Vol. 199, pp. 321-333, 2018. https://doi.org/10.1016/j.jclepro.2018.07.169
[66] ROSAS-SATIZÁBAL, D., RODRIGUEZ-VALENCIA, A.: Factors and policies explaining the emergence of the bicycle commuter in Bogotá, *Case Studies on Transport Policy*, Vol. 7, No. 1, pp. 138-149, 2019. https://doi.org/10.1016/j.cstp.2018.12.007
[67] GUZMAN, L.A., OVIEDO, D.: Accessibility, affordability and equity: Assessing “pro-poor” public transport subsidies in Bogotá, *Transport Policy*, Vol. 68, No. April, pp. 37-51, 2018. https://doi.org/10.1016/j.tranpol.2018.04.012

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