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

Javier Andres Calderon-Tellez, Milton M. Herrera, Alvaro Javier Salinas-Rodriguez

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, such as the Paris Agreement and the intergovernmental panel on climate change (IPCC).

Keywords: electric vehicle, low-carbon policy, energy transition, transport, simulation.

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 °C [2] as well as the Paris Agreement to reach global temperature below 2 °C [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 adopting 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 CO₂ emissions were from solid fuel consumption in Colombia and by 2016, its contribution to CO₂ 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 CO₂ 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 Medellín, 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 decarbonisation 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.
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 ($EV_p$) (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.

$$EV_p(t) = EV_p(t-1) + \int evr(t)(dt) \quad (1)$$

$$evr(t) = EV_p(t - \varphi) \quad (2)$$

Where,

$\varphi$: 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,
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.

![Motor vehicles classification](image)

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

### 3.2 CO₂ 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 43.8 [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].

\[
F = 5.32 \ln \left( \frac{C}{C_0} \right) + 0.39 \left[ \ln \left( \frac{C}{C_0} \right) \right]^2
\]  

Where C represents the concentration of CO₂, while C₀ is equal to 278×10⁻⁶.

![Temperature sector adapted from Fiddeman’s model](image)

**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.
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 °C – or IPCC – limit global warming to 1.5 °C. 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 CO₂ emission levels.

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.
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.

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 1 Low carbon policy proposed

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Equation within the simulation model</th>
<th>Alternatives of low carbon policy for the EVs transition ($\varphi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Business as usual – BAU</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Uncertainty for infrastructure development</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Searching to align with the worldwide environmental policy</td>
<td>$e_{\text{vr}}(t) = E_{\text{V}}p(t - \varphi)$</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Optimistic development in infrastructure and tax reduction to the incentive in the acquisition of EVs</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

### Table 2 Electric vehicles transition by 2050

<table>
<thead>
<tr>
<th>Scenario</th>
<th>EVs for 2050 in million</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.2</td>
</tr>
<tr>
<td>2</td>
<td>13.7</td>
</tr>
<tr>
<td>3</td>
<td>15.2</td>
</tr>
<tr>
<td>4</td>
<td>16.8</td>
</tr>
</tbody>
</table>
4.2 CO$_2$ emission levels

The trend of CO$_2$ 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 CO$_2$ emission levels for all scenarios is very high. Scenario 1 represents the highest increase, while scenario 4 represents the lowest increase for the CO$_2$ 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 CO$_2$ 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 CO$_2$ emission levels trend until 2050 in Bogota](image)

Table 3 shows the CO$_2$ emission levels by 2050 for each of the scenarios. The fourth scenario shows a decrease in CO$_2$ 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>
<thead>
<tr>
<th>Scenario</th>
<th>CO$_2$ emission for 2050 in kilotons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>114,266</td>
</tr>
<tr>
<td>2</td>
<td>44,392</td>
</tr>
<tr>
<td>3</td>
<td>30,417</td>
</tr>
<tr>
<td>4</td>
<td>16,442</td>
</tr>
</tbody>
</table>

Table 3 CO$_2$ emission levels by 2050

An analysis of the behaviour of temperature for future years is presented in Figure 8. Both the CO$_2$ 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.

4.3 Temperature variation
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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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature by 2050 (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.58</td>
</tr>
<tr>
<td>2</td>
<td>16.40</td>
</tr>
<tr>
<td>3</td>
<td>16.32</td>
</tr>
<tr>
<td>4</td>
<td>16.21</td>
</tr>
</tbody>
</table>

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 °C, the second scenario is 1.91 °C, the third scenario is 1.83 °C, and the fourth scenario is 1.72 °C.

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

Acknowledgement

Universidad Militar Nueva Granada (Grant, IMP-ECO-3402 partially supported this research). We thank anonymous reviewers for their comments on an earlier version of the manuscript.

References


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