Dynamical systems approach in automobiles technological transition from environmental drivers

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Abstract. The effects of climate change have led us to identify the need to minimize emissions, particularly in the transport sector. However, the demand for cars has increased and, the only alternative is the technological transition towards zero-emission technologies such as electric cars. This document proposes a mathematical model based on system dynamics to evaluate with dynamical systems the technological transition of automobiles from environmental drives. The results show bifurcations of codimension 2 between 4 different types of phase portraits, each of which allowed to identify a different type of transition. It is concluded that the demand for each technology and its useful life will determine its permanence in the market, but that each of these gives rise to environmental impacts that will guide the preferences of consumers, with the possibility that there is a loss in the motivation of consumers generated by the emergence of some other type of alternative, perhaps such as active mobility.

1. Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) report showed us a bleak future, allowing us to identify the need for an energy transition to counteract the effects of climate change [1]. This energy transition requires actions from different sectors, mainly focused on achieving a sustainable society. Among the sectors, the transport sector is responsible for more than 20% of global greenhouse gas (GHG) emissions [2]. Rapid urbanization has contributed to the growing demand for automobiles, a large majority of which run on fossil fuels, leading to air pollution and a deterioration in the quality of life [3,4].

One way to mitigate $CO_2$ emissions from the transportation sector are to meet the growing demand with alternative automobile, such as hybrid (HEV), plug-in hybrids (PHEV), and battery-electric automobile (BEV), which could turn them into a determining factor for those whose vehicle replacement criteria is the environmental impact [5–10]. According to [7], it has shown by a well-to-wheels analysis that battery electric automobile BEVs significantly reduce 32% $CO_2$ emissions compared to their conventional counterparts [7].

Electric automobile with low-carbon sources of electricity generation, such as renewable energy, offer the potential to reduce GHG emissions and exposure to vehicle tailpipe emissions [11–14]. Likewise, it is relevant to highlight that, unless countries with a high $CO_2$ emission seek significant decarbonization of their energy generation matrix, they will not be able to take full advantage of the capacity of electric automobile to reduce $CO_2$ emissions from transport [15–18].
With increased charging infrastructure, improved power generation efficiency, the inclusion of renewable energy, and reduced battery cost is expected the profitability of electric automobile to improve significantly over the next decade and, this will contribute to the decrease in emissions [14]. However, the transition to electric automobile has a series of relevant conditions that could delay it. One of them is battery management since these are the vehicle’s energy source, and the GHGs associated with the materials and the production of lithium-ion batteries represent between 2% and 5% of the emissions of the vehicle the life cycle of HEV, PHEV, and BEV [9]. Battery management is a relevant issue considering that from mineral exploitation to final disposal, it presents environmental impacts.

This document proposes a mathematical model based on system dynamics to evaluate with dynamical systems the technological transition of automobiles from environmental drivers, thus becoming a benchmark to propose mitigation and adaptation measures to climate change from the road transport sector in consideration of the energy that these could use.

2. Methodology

Next, the modeling based on system dynamics is presented for representing the technological transition of automobiles from environmental drives, and the dynamical systems analysis.

2.1. System modeling

To obtain the mathematical model, the level and flow diagram in Figure 1 has been constructed, in which only two categories of automobiles have been considered: conventional and electric; each of them has an input and output that depends on production and scrap rates. However, each of these categories of automobiles generates environmental impacts due to emissions or waste disposal that affect user compliance and promote technological leap, by the assumption that users decide to make the transition only for reasons of environmental awareness.

![Figure 1. Stocks and flows diagram of the automobile technology transition from environmental driver.](image-url)
The change over time (represented by a point on the variable) of conventional automobiles ($x$), given in (automobiles), is the difference between automobiles entering the market (CAI) and coming out of the market (CAO), given in (automobiles/year). On the other hand, the change ($d/dt$) of electric automobiles ($y$), given in (automobiles), is the difference between the automobiles that enter the market (EAI) and come out of the market (EAO), given in (automobiles/year); in this way, we obtain the level Equation (1).

$$\dot{x} = CAI - CAO,$$
$$\dot{y} = EAI - EAO.$$  (1)

Equation (1) are defined in such a way that, the increase in the quantities of each vehicle category depends on the disagreement that users have with the other category, and the decrease depends on an average depreciation, as in Equation (2).

$$CAI = a \cdot x \cdot (1 - CEA) \quad ; \quad CAO = b \cdot x,$$
$$EAI = c \cdot y \cdot (1 - CCA) \quad ; \quad EAO = d \cdot y,$$  (2)

where $a$, $b$, $c$ and $d$ are exchange rates given in ($\text{year}^{-1}$), and the conformities with each category depend on the closeness of the emissions ($E$), given in ($\text{TonCO}_2/\text{year}$), or hazardous waste ($W$) disposal, given in ($\text{TonC}/\text{year}$), with an allowable limit value (emissions limit $N$, given in ($\text{TonCO}_2/\text{year}$), and hazardous waste ($W$) limit, given in ($\text{Ton}/\text{year}$)) that could be agreed through national or international environmental commitments. In this way, compliances, emissions and hazardous waste are defined as Equation (3).

$$CEA = W/L \quad ; \quad CCA = E/N,$$

$$E = \epsilon \cdot x \quad ; \quad W = \rho \cdot y,$$  (3)

where $\epsilon$ and $\rho$ are exchange rates given in ($\text{TonCO}_2/(\text{automobile} \cdot \text{year})$) and ($\text{Ton}/(\text{automobile} \cdot \text{year})$), respectively. Finally, by replacing the equations, the mathematical model of this work is obtained Equation (4).

$$\dot{x} = x(\alpha - \delta y),$$
$$\dot{y} = y(\beta - \lambda x),$$  (4)

with $\alpha = a - b$, $\beta = c - d$, $\delta = a\rho/L$, and $\lambda = c\epsilon/N$.

2.2. Dynamical systems analysis
From the identification of the equilibrium points of the obtained system and the analysis of its stability, two parameters were identified that give rise to codimension 2 bifurcations that were not typified, but which gave rise to the discussion to be conclusive about the vehicular transitions.

The system of Equation 4 has the equilibria $Eq_1(0, 0)$ and $Eq_2(\beta/\lambda, \alpha/\delta)$, each of which has a stability that it depends on the values of the $\alpha$ and $\beta$ parameters. For the equilibrium $Eq_1$ the eigenvalues are $\alpha$ and $\beta$, while for the equilibrium $Eq_2$ the eigenvalues are $\pm\sqrt{\alpha\beta}$. This leads to four cases, each of which is presented in Figure 2 and Figure 3.
Figure 2. Case 1 simulations; this case occurs when vehicle entry rates are higher than exit rates in both categories: (a) and (b) both technologies grow but finally the conventional one dominates, while in (c) and (d) the opposite happens; (e) and (f) both technologies decrease but the electric one manages to recover, while in (g) and (h) the opposite happens.
Figure 3. Simulations for the cases 2, 3, and 4: this figure corresponds to another case of entrance rates growth than out rates in both automobile categories: (a) and (b) the scrapping of conventional automobiles is greater than the entry into the fleet (sales), while in (c) and (d) sales of conventional automobiles are greater than their operating output (scrap), which increases the number of vehicles in the fleet; (e) and (f) the lack of interest in the two technologies can be seen, causing their disappearance.

3. Results and discussion
The results and discussion of results presented in this section are based on the analysis for the transitions of the 4 cases that have been found by the analysis of the stability of the equilibrium points found, see Figure 2 and Figure 3, considering its interpretation for the non-negative space of the state variables exclusively, because it lacks a sense for the application of the other regions of the state plane.
3.1. Case 1

Case 1 consists of a stable focus at the origin and a saddle-node in the non-negative space of the state variables. From the application perspective, this case is interesting because the stable manifold and the unstable manifold of the saddle node define four regions of interest for the discussion of transitions, but particularly because the stable manifold partitions the non-negative region into two zones that determine the dominance of one or another technology. If the initial condition is located on the left side of the stable range, the electric automobiles participation will be the predominant one, while if the initial condition is located on the right-hand side, the conventional automobiles participation will be the predominant one.

In Figure 2 each of the first case possibilities and the evolutions for the 4 regions defined by the stable and unstable varieties of the saddle-node has been presented. The discussion in each of these areas (sub-cases) is presented below. In the Figure 2(a), case 1.1 is related, in which the initial condition is located on the right side of the stable variety of the saddle-node, at a point where there are few conventional automobiles and very few electric automobiles.

In Figure 2(b), there is an increase in conventional technology (time series x) while, although electric cars (time series y) seem to increase at the same time as the other technology, they do not exceed a maximum value that leads them to disappearance. The growth in the first phase of electric automobiles that the simulation shows, would respond to the benefits attributed to it in terms of emissions. For the second phase (after reaching the maximum value), is inferred that buyers with environmental commitment prefer to give up the two technologies, thus avoiding promoting mining (lithium) and its inadequate final disposal, while others continue to buy conventional vehicles.

In the Figure 2(c), you can see, case 1.2, which shows an inverse behavior to that presented in case 1.1. In this, the initial condition is located on the left side of the stable variety of the saddle-node, at a point where there are few electric automobiles and very few conventional automobiles. In Figure 2(d), you can see the result for the initial conditions in this region, in which, for the first phase, the two technologies increase in time until only the conventional technology reaches a top and converges to its disappearance. In this case is inferred that pollution by atmospheric emissions is understood to be much more dangerous than that related to waste disposal, fundamentally because it is the main cause of global warming and the consequences that this generalized increase in temperature on the planet causes on all vital activities for the human being. That is, in a balance between the two evils, the less shocking have been select.

The Figure 2(e) represents case 1.3, in which the initial condition is located on the left side of the stable variety of the saddle node, showing high participation of both electric and conventional automobiles. In this case, the Figure 2(f) shows a pronounced decrease is evident for conventional technologies, probably due to their responsibility for GHG emissions, which discourages their sale. In the case of electric automobiles, its behavior is very particular, it shows a slight drop, in this case, related to the life cycle of the batteries, and then it recovers, probably trying to supply the total demand for automobiles.

Finally, the Figure 2(g) represents case 1.4, which exhibits a behavior contrary to that shown by case 1.3. Here, as can be seen in the Figure 2(h), conventional automobiles reveal a temporary drop, to later recover, supplying all the demand, while electric vehicles are not successful in the market and disappear. The motivations for this decrease in demand can be diverse. For example, manufacturers currently offer a guarantee of 8 years of useful life for batteries, but after this time the user will not know what to do with the battery and will be restricted to the procedure defined by each country for its disposal. These conditions the interest of buyers who make their decisions with an environmental interest, in acquiring an electric automobile, and again promoting the purchase of conventional automobiles. On the other hand, the mathematical analysis also recognized other cases that could reflect the behavior of the technological transition of automobiles as shown in Figure 3 and is presented below.
3.2. Case 2
Case 2 is represented in the Figure 3(a), Figure 3(b). In this case, the scrapping of conventional automobiles is greater than the entry into the fleet (sales), probably related to the age of the fleet that leaves circulation and is not compensated with more conventional automobiles due to less interest in their acquisition. This, in turn, promotes the sale of electric cars, causing a significant increase. Environmental interests move this scenario in favor of the sale of electric automobiles, considering only the decrease in emissions from the transportation sector.

3.3. Case 3
In case 3, represented in the Figure 3(c), Figure 3(d), behavior contrary to case 2 is evidenced. In this case, sales of conventional automobiles are greater than their operating output (scrap), which increases the number of vehicles in the fleet. On the contrary, the operation output of electric automobiles is considerable than sales, which causes them to decrease significantly until they disappear, this in turn driven by the lack of interest in their purchase.

3.4. Case 4
Finally, in case 4 represented in the Figure 3(e), Figure 3(f), the lack of interest in the two technologies can be seen, causing their disappearance. In this case, the purchased ones consider that no negative environmental effect should be prioritized over the other, losing interest in these mobility alternatives and migrating to others such as active mobility or the use of public transport.

4. Conclusions
The explanatory model of automobile technology transitions from environmental determinants that have been developed in this article has made it possible to identify that there are different possibilities for the evolution of these transitions, taking bifurcation parameters as leverage points of the trend behavior of this system that depends on the demand and the useful life of the two automobile technologies studied. In this sense, the analysis based on dynamical systems is enriching for decision-making, allowing to lead guidelines that anticipate transitions and their consequences, giving rise to more appropriate procedures. It will have to be decided which scenario is better from the perspective of operability and environmental functionality, generating incentives that decisively benefit one of the two technologies or its disappearance (hence, for future work, active mobility will be included in the analysis).

Finally, the energy transition of the transport sector is a priority step in the decarbonization of anthropogenic activities to tackle climate change. However, this work shows that there are still many challenges to reducing or eliminating the impacts that energy systems have on nature. This raises questions about energy sources, materials used, processes efficiency, etc. In this way, this work reinforces the evidence that the present energy solutions are short-term and present the challenge to physicists and engineers to propose solutions that satisfy long-term multidimensional needs.

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