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Policy analysis to boost the adoption of alternative fuel vehicles in the Colombian market

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Abstract

The growing concerns about the climate change, the characteristics of the transport sector and its future trend, have made this sector be considered relevant in the policy analysis that promote the low carbon economy. The development of alternative fuel vehicles is one of these policies. However, although the diffusion of clean technologies has been studied for the academy community, and is receiving major attention of the governments, industries and stakeholders, both the adoption process of these technologies in developing countries and the effectiveness of the policies for boost the adoption in the market are low known. This research presents a conceptual approach that involves a design and use of a system dynamics simulation model based on. Simulations with two different policies: fiscal and communication were carried out. The results show that the communication policy is more effective than the fiscal policy when we try to impulse a model of low carbon private transport in the Colombian market.

Keywords: System dynamics, Simulation, Modeling, Diffusion, Adoption, Alternative fuel vehicles, Policy analysis.

Introduction

Policy analysis is very important before implement them in complex and high uncertainty environments. One of the main reasons why policies fail is do not consider the complex characteristics of the environment in which policies are made (Forrester, 1958, 1995; Ghaffarzadegan, Lyneis, & Richardson, 2010; J. D. Sterman, 1989; John D Sterman, 2000). The policy resistance arises of the feedback present in the complex systems. An appropriate policy analysis prior to implementation often gives some ideas on how to intervene the system to avoid such resistance.

The innovation diffusion is a complex and highly uncertain phenomenon (Peres, Muller, & Mahajan, 2010). This phenomenon is characterized by nonlinear dynamics, (Shepherd, Bonsall, & Harrison, 2012), interactions between the agents and feedback between the variables (Meyer & Winebrake, 2009; Struben & Sterman, 2008). Although the adoption analysis has been studied for more of 40 years, is missing build models applied to specific industries in developing countries. Recent reviews in the study of diffusion of innovations have identified three major challenges in this area of research (Atabani, Badruddin, Mekhilef, & Silitonga, 2011; Kiesling, Günther, Stummer, & Wakolbinger, 2011; Montalvo & Kemp, 2008; Rao & Kishore, 2010). First one is to build models applied to developing countries, second one is to incorporate elements of bounded rationality in the models, and third one is to report the use of diffusion models in practical applications in specific industries.

In the automotive industry, the energy outlook for private transport offers multiple options both conventional and alternative. Recent investigations identify bio-fuel (Sobrino, Monroy, & Pérez, 2010), natural gas (Vergara, 2009), electricity (Høyer, 2008) and hydrogen (Baptista, Tomás, & Silva, 2010; Bento, 2010) as potential alternative fuels. Nowadays there are many questions about which option will be dominant.

The study of diffusion of alternative options has focused on the analysis of factors that might promote and block their adoption. In general, the factors can be classified, as proposed Wejnert (2002), in innovation characteristics, innovative characteristics, and environment characteristics. In particular, the

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barriers can be classified in financial, political, regulatory and legal, technological, public acceptance, and market availability (Browne, O'Mahony, & Caulfield, 2012; Eppstein, Grover, Marshall, & Rizzo, 2011; Franco & Figueroa, 2008; Montalvo & Kemp, 2008; Steenberghen & López, 2008; Wiedmann, Hennigs, Pankalla, Kassubek, & Seegebarth, 2011; Zubaryeva, Thiel, Barbone, & Mercier, 2012).

The policies to boost the adoption should focus in overcome the identified obstacles. The main challenge facing the alternative fuel vehicles is to break the barriers to entry into the market created by the conventional industry (Struben & Sterman, 2008). There are policy options to break the closed structure of the market (Kwon, 2012). According to Steenberghen & López (2008) a combination of several strategies and instruments is required to achieve the goal. However, little is known about the effectiveness of the proposed policies. The research has been focused in identify the strategies more than assessment them. In this way, there are few studies that explore the effectiveness of policies designed to boost the adoption of alternative fuel vehicles in developing countries.

The modeling of policies should help in the identified problem analysis. The simulation is a particular kind of modeling and introduces a new way to think about social and economic process, based on ideas about the emergent complex behavior (Gilbert & Troitzsch, 2005). This technique is gaining a growing acceptation in the academic community for studies like one we propose, that involves a complex phenomenon. Between all the simulation methods, we select system dynamics approach for analyze our problem. This approach allows built a clear and holistic vision of the problem, this vision helps to understand the system structure, to reply the system behavior, and to assess the effects of proposed policies.

Some authors has been used system dynamics to analyze the adoption of alternative fuel vehicles in developed countries: Struben and Sterman (2008) designed a dynamic model of the diffusion and competence of alternative fuel vehicles, but the authors do not analyze policies for boost the adoption in detail. After, Meyer and Winebrake (2009) modeled the dynamic of the diffusion of hydrogen vehicles in industrialized countries. Later, Stepherd et al (2012) developed a system dynamic model to analyze the adoption of electric vehicles in United Kingdom and focused in analysis of subsides. However, the dynamic behavior of the Colombian market cannot be inferred from the analysis of developed countries market. Colombia is a developing county and this introduces big financial, political, economic, and technological differences with developed countries. This environment impedes to explain the behavior of the Colombian market from the existent models.

This research formulates a model that relates the innovation diffusion with decision making dynamically, taking account bounded rationality elements. Moreover, pretends, based on the related academic literature, the development of a simulation model that allows see the evolution in time of the adoption of alternative fuel vehicles in the Colombian market. Finally, we intend to use the simulation model built for analyze and assess policies that boost the adoption.

In order to achieve the proposed objectives, this article proceeds as follows. First, we present the current situation from the tree research areas associated to this work: diffusion and adoption of innovations, transport sector outlook, and policies assessment. In the second section, we apply this conceptualization to develop a novel model that represents the phenomenon of alternative fuel vehicles adoption. The next section shows the simulation analysis from the discussion of the results obtained both the base case and policies applied. The final section summary the most relevant elements of the research.

The originality and importance of this research is based on the following elements:

- Development of an integrated model that combines diffusion and adoption of innovations with a discrete choice model that takes into account the bounded rationality of consumers.
- Observe the adoption of alternative fuel vehicles and explore the transition to low carbon private mobility in Colombia considering the system feedbacks and complexities.
- Evidence the behavior of the modeled system when we apply policies that boost the adoption of alternative fuel vehicles in order to compare effects and to define which policy is the best.

Current situation

In this section, initially we will realize on existing information and studies required for the adoption of alternative fuel vehicles and policy analysis to encourage adoption by dividing the review into three themes: diffusion and adoption of innovations, transport sector overview, and policies assessment. Then, the problem will be delimited from research questions in each research area. Finally, we present the formulation of the basic dynamic hypothesis to represent the problem studied.

Diffusion and adoption of innovations

The analysis of the diffusion and adoption of innovations remains an important research topic (Meade & Islam, 2006). The literature in this field can be divided in two lines of research: innovation diffusion and technology adoption. On one hand, the diffusion of innovations has enjoyed a strong academic and practical interest since 1960 when the first mathematical models were developed (Meade & Islam, 2006; Peres et al., 2010; Rao & Kishore, 2010). These models capture the trend of the spread in the form of differential equations from adoption rates that depend on the context. In the other hand, the modeling of individual adoption decisions began in the early 70s and has been an important field of study for the past 20 years (Cadavid & Franco, 2012). The diffusion of innovations characterized the mechanisms and patterns of diffusion technology adoption while seeking to understand and characterize the structure of decision making (Cadavid & Franco, 2012). Arguably diffusion is a function of the adoption.

The adoption of an innovation, and hence its diffusion is influenced by many factors that can be grouped into three categories: characteristics of innovation, characteristics of innovators and environment characteristics as presented in **Table 1.** These factors may help or hinder the adoption. The development of a framework integrating these elements into a model applied to a specific industry, especially in developing countries is necessary.

Table 1. Classification of attributes relevant to the choice of technology

Category	**Attributes**
Characteristics of innovation	Purchase price, Cost of fuel, Autonomy, Emissions, Availability of supply, Refueling time
Characteristics of innovators	Socioeconomic and demographic conditions, Social interactions, Perceptions, Familiarity
Environment Characteristics	Policies and incentives, Culture and Exposure to different platforms (marketing, mass communication and word of mouth), Economies of scale, Competition and market structure, Regulatory framework

Source: the authors. Based on: (Egbue & Long, 2012; Kang & Park, 2011; Mabit & Fosgerau, 2011; MacVaugh & Schiavone, 2010; Montalvo, 2008; Rao & Kishore, 2010; Wejnert, 2002; Zubaryeva et al., 2012)

Transport sector overview

Current features of the transport sector and future development prospects have done there is growing interest in the research area focused on its evolution. In the literature can be identified two competing technologies: internal combustion vehicles and vehicles powered by fuel cells, as a mixture of both are hybrid vehicles. Recent research highlights biofuels (Sobrino et al., 2010), natural gas (Vergara, 2009), electricity (Høyer, 2008), and hydrogen (Baptista et al., 2010; Bento, 2010) as potential fuels. To date, there are big questions about what will be the dominant technology. Studies have been applied to developed countries to respond to this research question. However, the analysis of developing countries is a special case which requires considering the specific market characteristics.

Policies assessment

In the review, we may identify multiple factors that act as barriers to the penetration of alternative vehicles into the market (Wiedmann et al., 2011). In fact, research on clean technology vehicles have focused on the analysis of such barriers. These barriers can be classified as financial, political, regulatory and legal, technological, public acceptance, and market availability as presented in **Table 2.**

The results of investigations have found that the main challenge for the transition to alternative vehicles is to break the barriers created by the traditional vehicle industry. It is expected that as these barriers are broken, the vehicles achieve greater market penetration (Eppstein et al., 2011; Zubaryeva et al., 2012). Considering the above, the policies designed to encourage preference for alternative fuel vehicles should be oriented, in principle, to break these barriers. In general, the policy decisions that consider such critical elements have had a high level of success (Egbue & Long, 2012).

Table 2. Barriers to the penetration of alternative vehicles into the market

Category	Barriers identified
Financial	Vehicle price, Cost of conventional fuel versus alternative fuel, Capital cost, Operational costs
Political, regulatory and legal	Regulatory framework, Lack of specific legislation, Planning restrictions, Lack of consistent regulatory standards, Weak or inconsistent policy signals
Technological	Competitiveness, Research and development, Fuel storage
Public acceptance	Attitudes and social values, Environmental awareness, Availability of information, Resistance to change, Risk aversion of new technology, Low level of visibility, and Public skepticism and inertia
Market Availability	Service stations limited, Supply system access, distribution and storage.

Source: the authors. Based on: (Browne et al., 2012; Eppstein et al., 2011; Franco & Figueroa, 2008; Montalvo & Kemp, 2008; Steenberghen & López, 2008; Wiedmann et al., 2011; Zubaryeva et al., 2012).

According to a study reported by Köhler et al (2009), the adoption of private vehicles with alternative fuels contributes to the transition to low-carbon mobility. This transition requires political and institutional changes that promote its diffusion and make it self-sustaining over time (Köhler et al., 2009; Markard, Raven, & Truffer, 2012; Steenberghen & López, 2008). For Steenberghen & López (2008), a combination of strategies and measures is required to increase the effectiveness of policies, and reach the goal of breaking the closed structure of the conventional vehicle market.

The policies to boost the low-carbon mobility fall into four categories: fiscal, physical, soft, and knowledge. **Table 3** summarizes the items belonging to each class. However, although there have been important research in this field, little is known of the effectiveness of the proposed policies to encourage the adoption of alternative fuel vehicles (Cadavid & Franco, 2010).

Table 3. Classification of policies and instruments to encourage the adoption of AFV

Policies	Instruments
Fiscal	Taxes, Subsidies, Charges, Standards
Physics	Integrate with public transport, Better land use, Road construction
Soft	Advertising, Marketing
Knowledge	Research and development in clean technologies

Source: the authors. Based on: (Atabani et al., 2011; Mueller & De Haan, 2009; Santos, Behrendt, Maconi, Shirvani, & Teytelboym, 2010; Santos, Behrendt, & Teytelboym, 2010; Yeh, 2007)

Research Problem

In the review of literature is possible identify a growing interest in the research area focused on the development of the transport sector, taking into account the characteristics of the sector and the prospects for future development. In this line of action can be grouped researches concerned about the penetration of vehicles with clean technology into the market and the study of mechanisms to encourage their adoption. However, on these topics are some elements that remain unresolved and are the basis of the research problem discussed in this article. In relation to the diffusion and adoption of innovations, do not know how will be the transition process and adoption of new technologies in developing countries. Associated with the overview of the transport sector, do not know which technology will dominate the private transport sector in developing countries. And regarding the evaluation of policies, has not been studied what is the effectiveness of the instruments designed to encourage the adoption of low carbon transport particularly in developing countries.

This research analyzes the adoption of alternative fuel vehicles in the Colombian market. In this market, the private transport sector has had a 160% growth in the last decade (UPME, 2010a). This sector is characterized by the traditional dependence of fossil fuels, and is responsible of 39% of country energy consumption (UPME, 2010b). This market characteristics, accompanied by the worry about climate change, the high levels of population and noise in the cities, and the national energy policy have led to consider natural gas vehicles (NGV) and plug-in electric vehicles (PEV) as future private mobility options.

NGV have been introduced to the market 15 years ago, they have a range distribution network and they have been promoted by different agreements between private and public entities (Vergara, 2009). In relation to PEV, until now energy sector and automotive companies have signed cooperation agreements for introduce 250 vehicles as a pilot proof in 2013. This has the purpose to assess and analyze the market viability (CODENSA, 2011; EPM, 2011). Based on the above, this research will study the dynamics of the adoption of natural gas vehicles and plug-in electric vehicles in the Colombian market, taking into account the current market characteristics and the expectations associated to the entering of electric vehicles into the system.

Basic dynamic hypothesis

The dynamic causal structure that explains the behavior of the diffusion of alternative vehicles is illustrated in **Figure 1**. As shown in the figure, the dynamic system is described by eight cycles of feedback through which relate the different elements of the system.

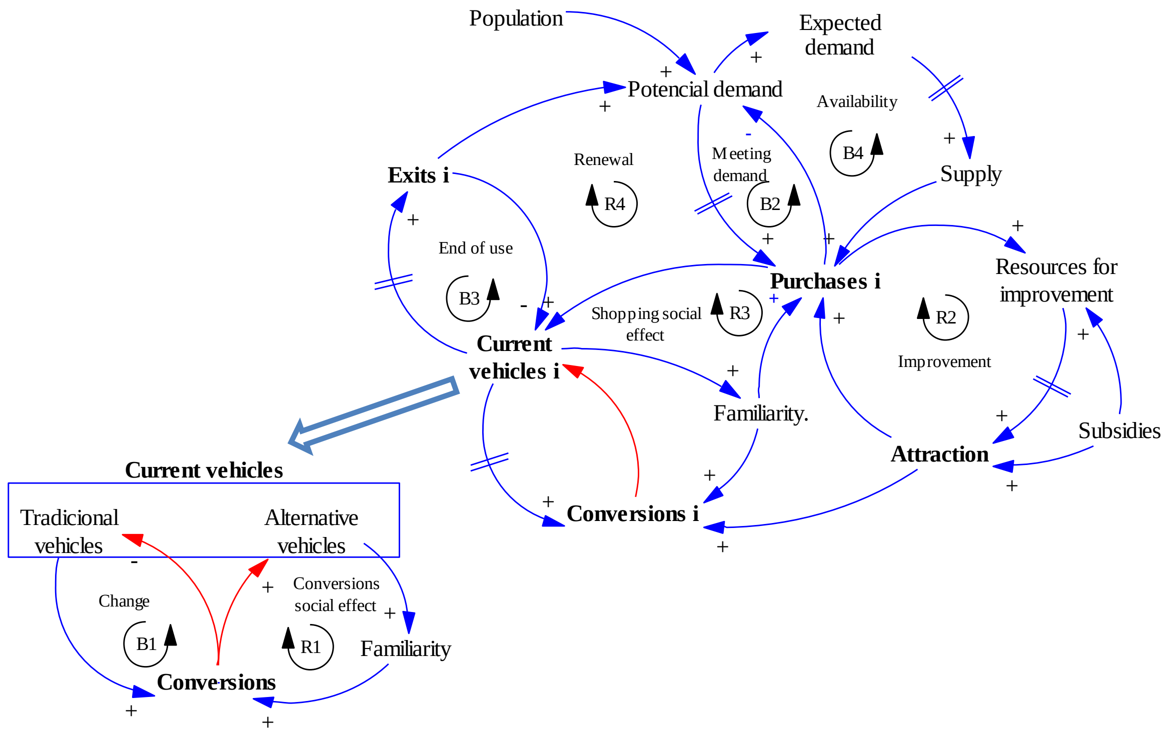

Fig. 1. Basic structure feedback. In this figure are shown the eight feedback loops that define the dynamics of the diffusion of alternative fuel vehicles. In the lower right illustrates the two current vehicles categories (traditional vehicles and vehicles). Source: the authors using Vensim® PLE for Windows Version 5.11A from Ventana Systems, Inc.

Current vehicles have two main categories, *traditional vehicles* represented by gasoline vehicles and *alternative vehicles* represented by natural gas vehicles and plug-in electric vehicles.

The *conversions*, from *traditional vehicles* to *alternative vehicles*, which are explained by the cycle "change" (B1), depend on the amount of *traditional vehicles* in the system. Both *conversions* and *purchases* are a function of *familiarity* and *attraction* of the costumers with of the alternatives.

As *traditional vehicles* are increased *conversions* rise. This has two effects: on one hand it reduces the quantity of *traditional vehicles* and on the other hand increases the quantity of *alternative vehicles*.

When *conversions* are elevated in the system, the amount of *alternative vehicles* increases, consequently *familiarity* rises and this result in higher *conversions* post. These relationships are illustrated with the cycle "conversions social effect" (R1), this cycle allow us to study the effect of *familiarity* on the *conversions*.

An important variable in the dynamics of new technologies is *improvement.* In the causal diagram, cycle "improvement" (R2) models the progress of technologies as they improve their attributes to become more attractive. Resources for this *improvement* come from a percentage of *purchases* and *subsidies*.

The *familiarity* of each technology is modeled as a function of *current vehicles* in the market. This modeling can be seen in the cycle "shopping social effect" (R3). The *demand* is met through purchases, as illustrated in the cycle "meeting demand" (B2).

The *purchases* depend on the *supply* of vehicles on the market, which is modeled as a function of the *expected demand* delayed by *production capacity* and *manufacturing time*. These relationships are presented in the cycle "availability" (B4).

Finally, the cycle "renewal" (R4) is evidence that the vehicle fleet is renewed as the vehicles are removed from the market by *accident* or *obsolescence*, and enter new vehicles through *purchases* or *conversions*.

Model description

This section uses contextualization presented above to establish the limits of the model. Subsequently dynamic structure is shown by the model representation in the diagram of flows and levels.

Overview

We build on the model developed by Walther et al (2010) and we adapted it to the Colombian market to establish the limits of our model. From a general perspective, our simulation model dynamically links four modules that interact with each other – "Industry", "Customers", "Installed base and infrastructure" and "Regulatory and financial framework"– as well as endogenous and exogenous parameters as illustrated in **Figure 2**.

Industry: The goal of the industry is to sell vehicles. To achieve this, the industry provides and promotes its products using different marketing and communication tools. Industry is the main actor in the research and development focused on improving vehicle attributes and directly influences the attractiveness of technologies. The industry is related to the other modules of the system in different ways:

- Industry must meet the financial and regulatory framework established in the market.
- Industry interacts with customers through the purchase and conversion decisions.
- Industry investments to increase the system infrastructure.

Customers: The goal of the customers is to purchase or convert a vehicle. These decisions are influenced mainly by the attraction and familiarity with the alternatives. Customers relate to the other modules of the system in different ways:

- Customers' decisions modify the installed base of vehicles.
- Customers are the direct users of the infrastructure.
- Customers receive information to industry through marketing tools that can influence their decisions.
- Customers access to credits and subsidies defined regulatory framework and financial.

Installed base and infrastructure: This module integrates the number of vehicles on the market and the infrastructure needed to supply them with fuel. In this module, the installed base is affected by the exogenous variables: vehicle useful life and accident rate. The infrastructure is affected by construction time and stations useful life. The number of stations is influenced by infrastructure investment decisions made by industry. The installed base changes with the purchase decisions and conversion decisions made by customers.

Regulatory and financial framework: This module contained essential elements for the development of fiscal and financial policies. The definition of the tax policy on imports and purchasing decisions affects the two modules related with this module: industry and customers. Subsidies for the purchase or conversion are oriented to customers. Subsidies for improvement are designed to support the industry.

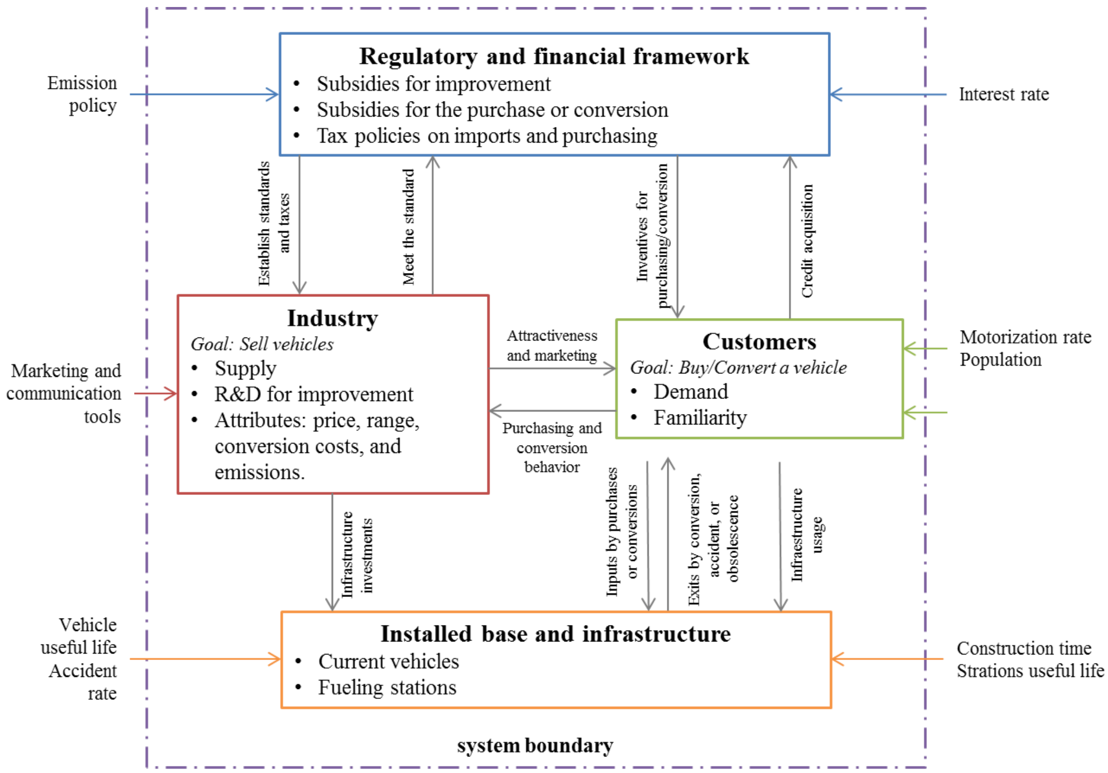

Fig. 2. Model overview. Four modules each one with endogenous and exogenous parameters. Adapted from (Walther et al., 2010)

Dynamic Structure

The most important elements of the structure of the system that relates the four modules are summarized in **Figure 3.** This figure shows a simplified version of the dynamic structure of the simulation model, that is, the sequence of actions occurring in the system. This subsection formalizes the basic dynamic hypothesis, based on the system equations, considering the state variables or levels, and flows.

The macrostructure of the model presented in **Figure 1** contains two natural candidates for level variables: *current vehicles*(V_i) y *potential demand*(D), these are the state variables of the system. The level of each variable is defined in terms of the flow variables associated to it. In addition to these operations on accumulations, the model of **Figure 4** shows diverse decision process, for example the *purchases*(P_i). Each process is modeled with a decision rule, that is, the definition of how the actors in this system act and decide, according to the modelers. Next, we describe the system of equations that define the levels in **Figure 4** and explain the associated decision rules.

Current vehicles(V_i) accumulate (integrate) net flows: *purchases*(P_i), *entering conversions*(EC_i), *leaving conversions*(LC_i), and *exits*(E_i) as shown in equation 1.

$$V_i = V_i(0) + \int_0^t (P_i + EC_i - LC_i - E_i)\, dt \qquad [vehicles] \qquad (1)$$

The purchase decision in each period is a function of *potential demand*(D), *probability of purchase*(Pp_i), *availability*(A_i) and *delivery time*(td) and as shown in equation 2.

$$P_i = Min\left(\frac{D * Pp_i}{td}, \frac{A_i}{td}\right) \qquad [vehicles/yr] \qquad (2)$$

The *probability of purchase* is modeled with the *familiarity* and the *purchase attractiveness.* The *purchase attractiveness* is calculated using a multinomial logit model with the following attributes: price, range, operating costs, maintenance costs, current stations, and emissions. The *availability* allows modeling the vehicle production capacity, and *delivery time* refers to the time it takes delivery of the vehicle.

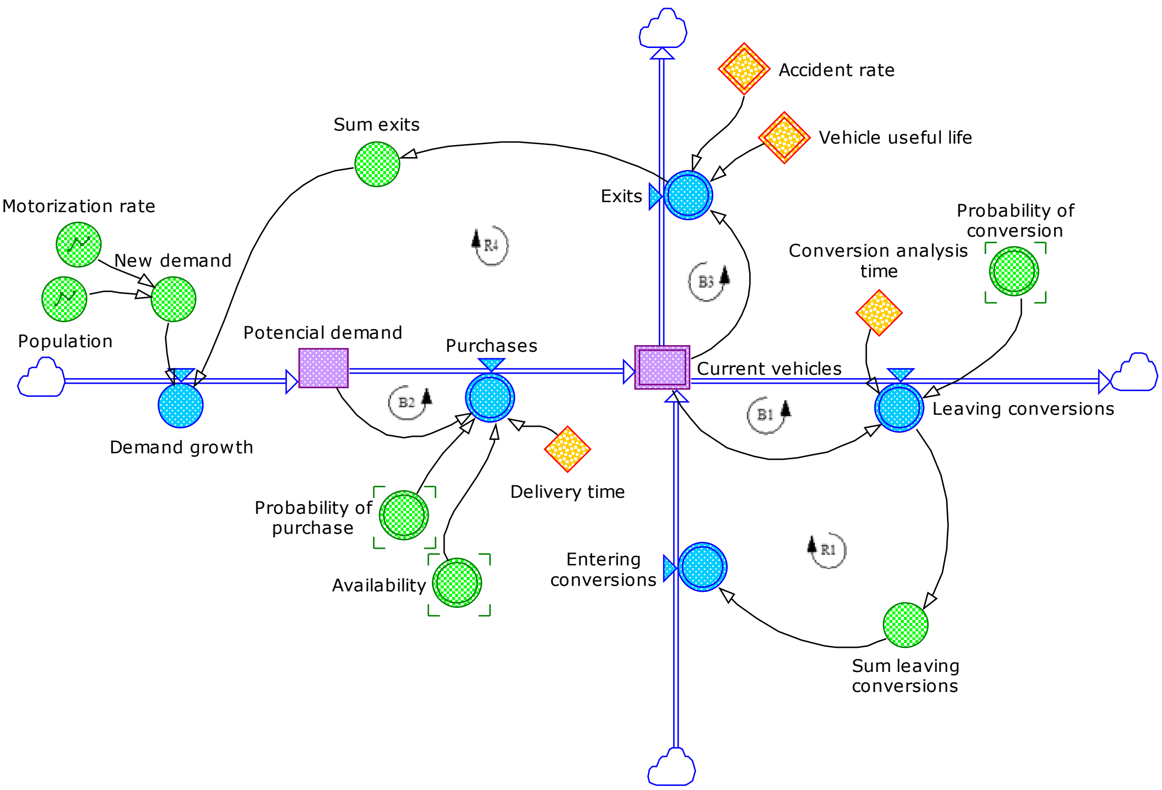

Fig. 3. Simplified structure of the simulation model. The simplified model has two levels and five flows. Current vehicles are the central level in the model by which we studied the evolution of adoption. In the figure it is possible to identify the balance cycles: B1, B2 and B3, and the reinforcing cycles: R1 and R4. Source: the authors using Powersim Studio 8 Academic from Powersim Software AS

To analyze the conversions of gasoline vehicles to NGV was necessary to consider two variables: *leaving conversions* and *entering conversions. Leaving conversions* depend on *current vehicles*, *probability of conversion*(Pc_i), and *conversion analysis time*(tc) of the way shown in equation 3. The *entering conversions* in each period are equal to *leaving conversions* of that period.

$$LC_i = \frac{V_i * Pc_i}{tc} \qquad [vehicles/yr] \qquad (3)$$

The *probability of conversion* is modeled with the *familiarity* and the *conversion attractiveness.* The *conversion attractiveness* is calculated using a multinomial logit model with the following attributes: equivalent annual cost, range, current stations, and emissions.

Finally, *exits* depend on *current vehicles*, the *accident rate*(ar), and the *vehicles useful life* (tl) as presented in equation 4.

$$E_i = V_i * ar + \frac{V_i}{tl} \qquad [vehicles/yr] \qquad (4)$$

The level of *potential demand* is increased by the inflow *demand growth*(Dg) and is reduced by the outflow *purchases* as shown in equation 5.

$$D = D(0) + \int_0^t (Dg - P_i)\, dt \qquad [vehicles] \qquad (5)$$

Demand growth depends on *New demand*(Nd) and *Exits*, as shown in equation 6. The *new demand* is defined in terms of the *population* and the *motorization rate.*

$$Dg = Nd + E_i \qquad [vehicles/yr] \quad (6)$$

Consumer decisions in the model (purchases and conversions) are a function of the attractiveness and the familiarity of technologies in competence. Following the theory of bounded rationality, the decision-making of adoption of alternative fuel vehicles is based on heuristics and these heuristics were modeled through the attractiveness and the familiarity.

The model described is a tool which combines the diffusion and adoption of innovations with a discrete choice model considering bounded rationality. The model can be used to observe the evolution in time of the adoption of alternative fuel vehicles in the Colombian market. This model can show the behavior of the system when introducing policies and strategies to encourage the adoption of these vehicles to compare effects and from these effects define what strategies will perform better. Results and analysis are presented in the following section.

Simulation analysis

A case study on the adoption of alternative fuel vehicles in the Colombian market was developed. This section initially describes the database used. Then, we present the simulation results for the base case against which we compare the results of two policies to encourage the adoption independently. The results allow us to define what policy will perform better and guide actions to respond appropriately to the system.

Database

The case analyzed in this research includes the traditional internal-combustion vehicles and two types of alternative fuel vehicles; natural-gas vehicles(NGV) and plug-in electric vehicles(PEV). The characteristics of the different alternatives analyzed were: price, operating cost, maintenance cost, equivalent annual cost (for conversions), emissions, range, time of supply, and fueling stations. Besides the above, in this research we studied the processes of improving these attributes via research and development. The case study is based on real information that was in part taken from public sources. A summary of the data used in the model is presented in Appendix A.

A time horizon of 20 years was analyzed. The simulation period starts in 2012. The model was implemented in Powersim Studio 8 Academic from Powersim Software AS. The graphs and analysis of results were developed using MS Excel.

Simulation results

The initial model results are shown in the **Figure 4**. We found that under actual conditions, in the next 20 years, the Colombian market will be dominated by traditional vehicles as can be seen in the **Figure 4a.** The amount of gasoline vehicles remains the market base throughout all the simulation. However, as time progresses, the slope of the line which describes its evolution is reduced. This phenomenon is mainly caused by an increase in the conversions to natural gas and replacement of these vehicles by others with alternative fuels.

The percentage of market share for each technology at the end of the simulation was 78.4% for gasoline vehicles, 17.9% for gas vehicles and 3.7% for electric vehicles. This market share reflects a strong dominance of conventional vehicles over alternative fuel vehicles.

In the **Figure 4b** is possible see that during the first 10 years simulated, there aren't almost PEV purchases. This behavior changes around 2020, after which, purchases of vehicles with alternative fuels increase. In general, the diffusion is slow and at the end of analyzed period PEV have very little market share. This can be explained by the barriers to entry into the market and the low consumer familiarity with the technology.

At the end of the simulation, the total of purchases in the market was distributed as follows: 74.7% were gasoline vehicles purchases, 16.5% were gas vehicles purchases, and 8.8% were electric vehicle purchases. This distribution indicates that the first option of most people, when they want to buy a vehicle, it is a conventional car.

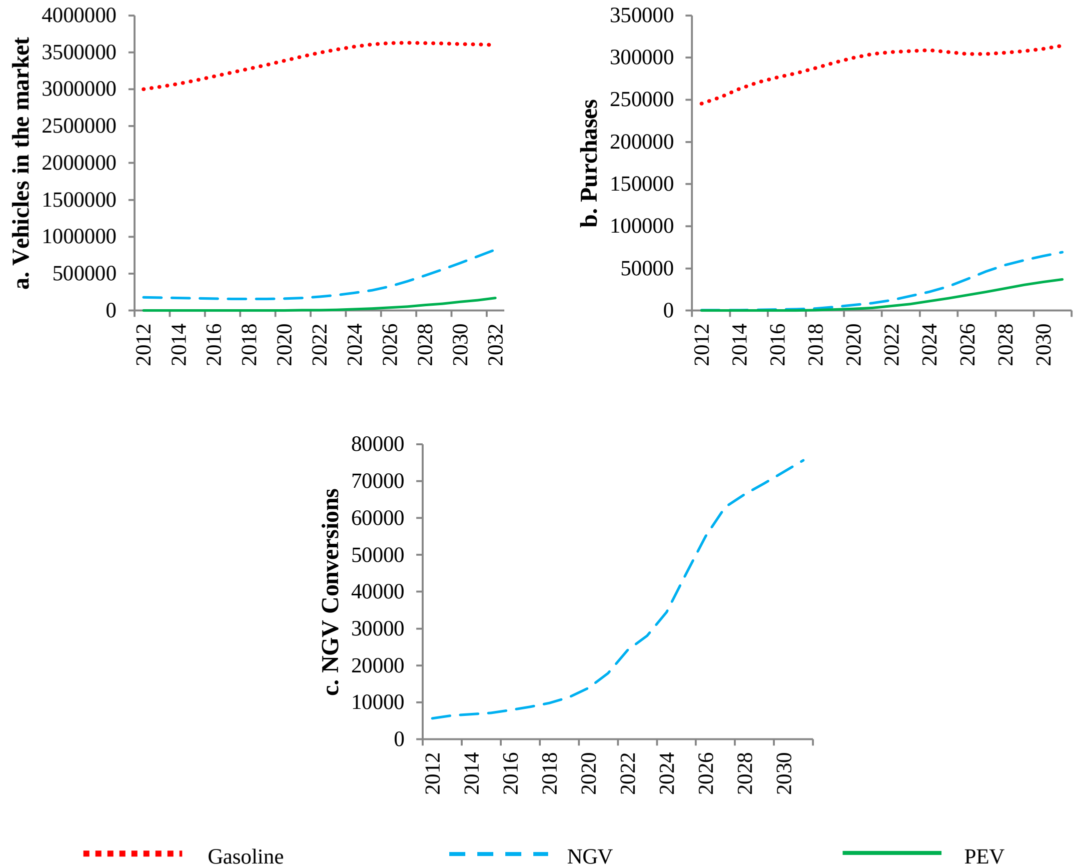

Fig. 4. Inital simulation results. Figures illustrate the evolution over time of the variables: Vehicles in the market (Figure 4a), Purchases (Figure 4b), and Conversions to NGV (Figure 4c). The x-axis measures time since 2012. Y-axis units are vehicles. The red dotted line represents gasoline vehicles, the striped blue line represents natural gas vehicles and the continuous green line represents electric vehicles. Source: the authors, from simulation results.

Vehicles converted to natural gas vehicles show a S-shaped behavior over time as seen in **Figure 4c.** Conversions are only gasoline vehicles to natural gas vehicles given the high costs and technical limitations involved in converting a gasoline vehicle to a plug-in electric vehicle.

Is important to emphasize three elements were evident throughout the simulation. First, a higher market share of conventional vehicles than the market share of vehicles with alternative sources. This dominance could be due to market barriers created by the long trajectory of the conventional vehicle industry. Second, it is possible to note the dominance of gas natural vehicles over electric vehicles. This phenomenon could be justified in the different periods of market entry of such vehicles. Undoubtedly, the initial income of natural gas vehicle allows this technology to enjoy some competitive advantages, particularly related to familiarity. Finally, results evidence recurrent growth in purchases of vehicles of all categories. This growth indicates that in the next 20 years, the market still has not reached its saturation level whereby the motorization rate in Colombia will be increasingly high.

Policy analysis

The public policies analysis developed in this document was oriented to overcome three types of entry barriers: financial, legal and regulatory policies, and public acceptance. Two policies were simulated; the results were compared with respect to the base simulation using the time to takeoff of the diffusion and market share as evaluation criteria.

Fiscal Policy

Figure 5 shows the results obtained after to apply a fiscal policy of financial and regulatory incentives. In one side, this policy consist on define a regulatory framework for import PEV without taxes and to develop a subsidy scheme for purchase PEV. In the other side, the policy consist on develop a subsidy scheme for conversions to NGV. In this way is possible overcome some financial and regulatory barriers that affect the diffusion of this technologies.

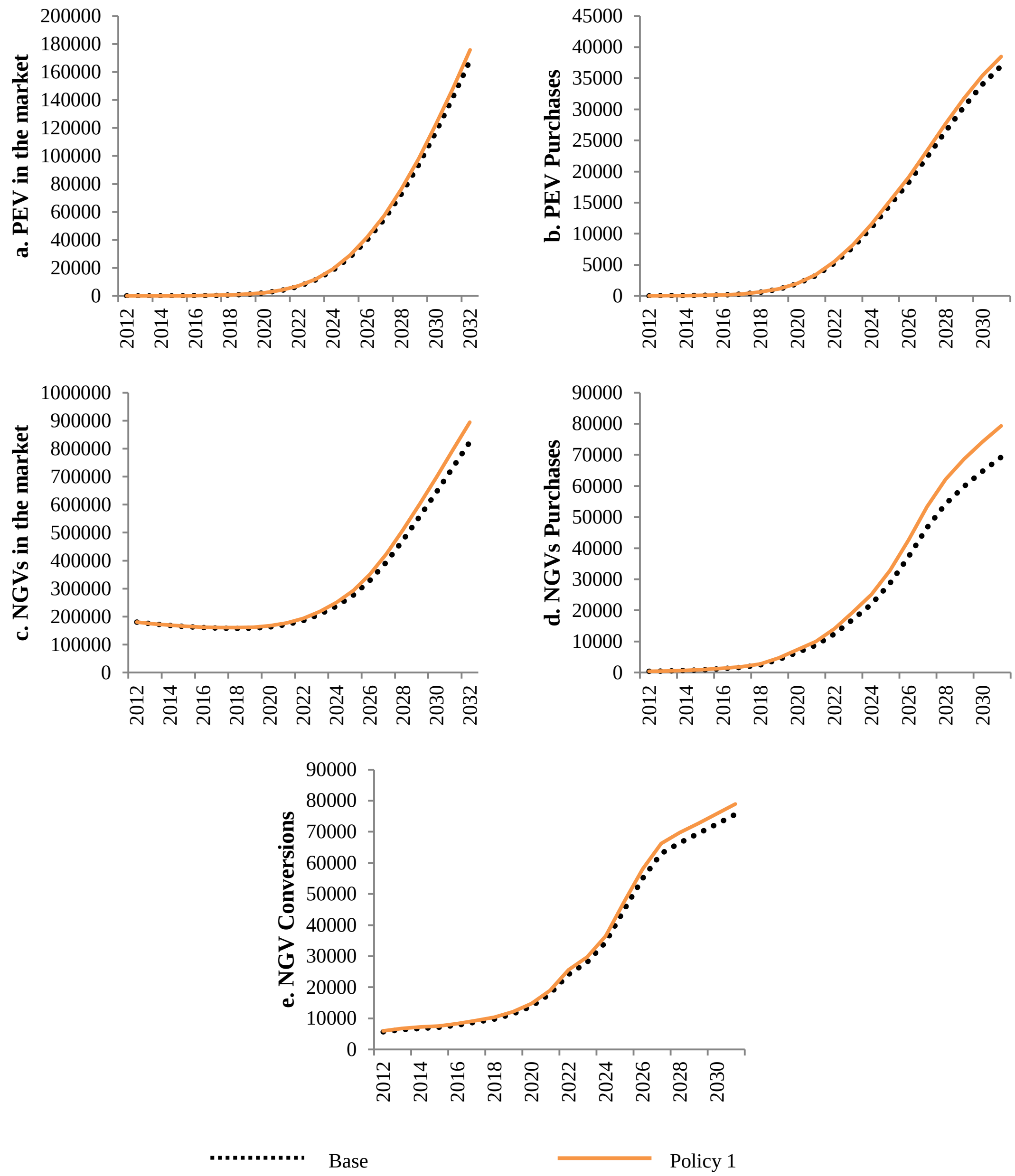

Fig. 5. Comparison between simulation results of Policy 1 and Base case. Figures shown, compared to the base case, the evolution over time of the variables: PEV market (Figure 5a), PEV purchases (Figure 5b), NGV market (Figure 5c), NGV purchases (Figure 5d), and NGV conversions (Figure 5e). The x-axis measures time since 2012. Y-axis units are vehicles. The continuous orange line represents the results of policy 1, and the dotted black line represents the base case results. Source: the authors, from simulation results.

As can be seen in **Figure 5b**, the PEV purchases are a little higher than in the base case with the implemented policy. However, the variations aren't significant; the diffusion curve slope remains very low, it reflects a slow adoption process. At the end of the simulated period, the number of PEV in the market (**Figure 5a**) only increased by 4.4% in comparison with the base case.

The dynamics of the number of NGV in the market (**Figure 5c**) described a slight increase that is more noticeable at the end of the simulated period. When comparing the results that illustrate the NGV purchases behavior (**Figure 5d**), and NGV conversions (**Figure 5e**), one can observe that the small increase in the number of vehicles is mainly due to purchases. At the end of the simulation, purchases increased by 14.6% compared to the baseline scenario, while conversions were up only 4.3%. As a combined result of these changes, the number of NGV in the market rose by 8.6%.

The percentage of market share for each technology at the end of the simulation was 76.7% for gasoline vehicles, 19.5% for NGV and 3.8% for PEV. This market share reflects that after applying policy 1 is still presented a strong dominance of conventional vehicles over alternative fuel vehicles.

At the end of the simulation, the total of purchases in the market was distributed as follows: 72% were gasoline vehicles purchases, 18.9% were NGV purchases, and 9.2% were PEV purchases. This distribution indicates that, after applying policy 1, the first option of most people, when they want to buy a vehicle, it is still a conventional car.

Communication Policy

The results obtained after apply a policy of communication, which promotes a model of sustainable mobility for the future, are shown in **Figure 6**. This policy consists on inform to the society about the technologies using marketing tools. This policy analysis is based on the decision making process reported in (Mueller & De Haan, 2009). According to Mueller & de Haan, the process consists of two phases; in the first phase, unknown alternatives are eliminated using simple rules, as result a choice set is obtained. In the second phase, the identification of the best alternative is performed using a multi-attribute compensating rule. The result of the process is the choice. In our case study, the universal set of choice is the set of all alternatives available in the market. While the choice set is the set of alternatives considered by the decision maker.

The aim of this policy is to make that the consumer considers AFV in his choice set when he wants to buy a private vehicle. Consumer information enables alternative fuel vehicles pass the first stage and are considered in the choice set become real and possible alternatives for the person who makes the decision. In our model, the filter of the first stage is represented by familiarity. Then in this scenario were used advertising and marketing campaigns to increase the consumer's familiarity with alternative fuel vehicles.

At the end of the simulated period, the number of PEV in the market (**Figure 6a**) increased by 27.4% in comparison with the base case. In the **Figure 6b** is possible see that the PEV purchases are higher than in the base case with the implemented policy. In net terms, the variation of the purchases was 30.5%. The diffusion curve slope is a little higher; but it continues reflecting a slow adoption process.

The dynamic of NGV in the market is illustrated in **Figure 6c**. Since 2018, it is possible to differentiate the curves illustrating the results of the base case and the implementation of the policy, NGV diffusion takes more strength. This change in behavior is due to both NGV purchases (**Figure 6d**) and NGV conversions (**Figure 6e**) that at the end of the simulated period increased by 33.8% and 35.2% respectively in comparison with the base case. As a combined result of these changes, the number of NGV rose by 34.8%

The percentage of market share for each technology at the end of the simulation was 71.1% for gasoline vehicles, 24.2% for NGV and 4.7% for PEV. This market share reflects that after applying policy 2 is still presented a strong dominance of conventional vehicles over alternative fuel vehicles.

At the end of the simulation, the total of purchases in the market was distributed as follows: 66.5% were gasoline vehicles purchases, 22% were NGV purchases, and 11.5% were PEV purchases. This distribution indicates that, after applying policy 2, the first option of most people, when they want to buy a vehicle, it is still a conventional car.

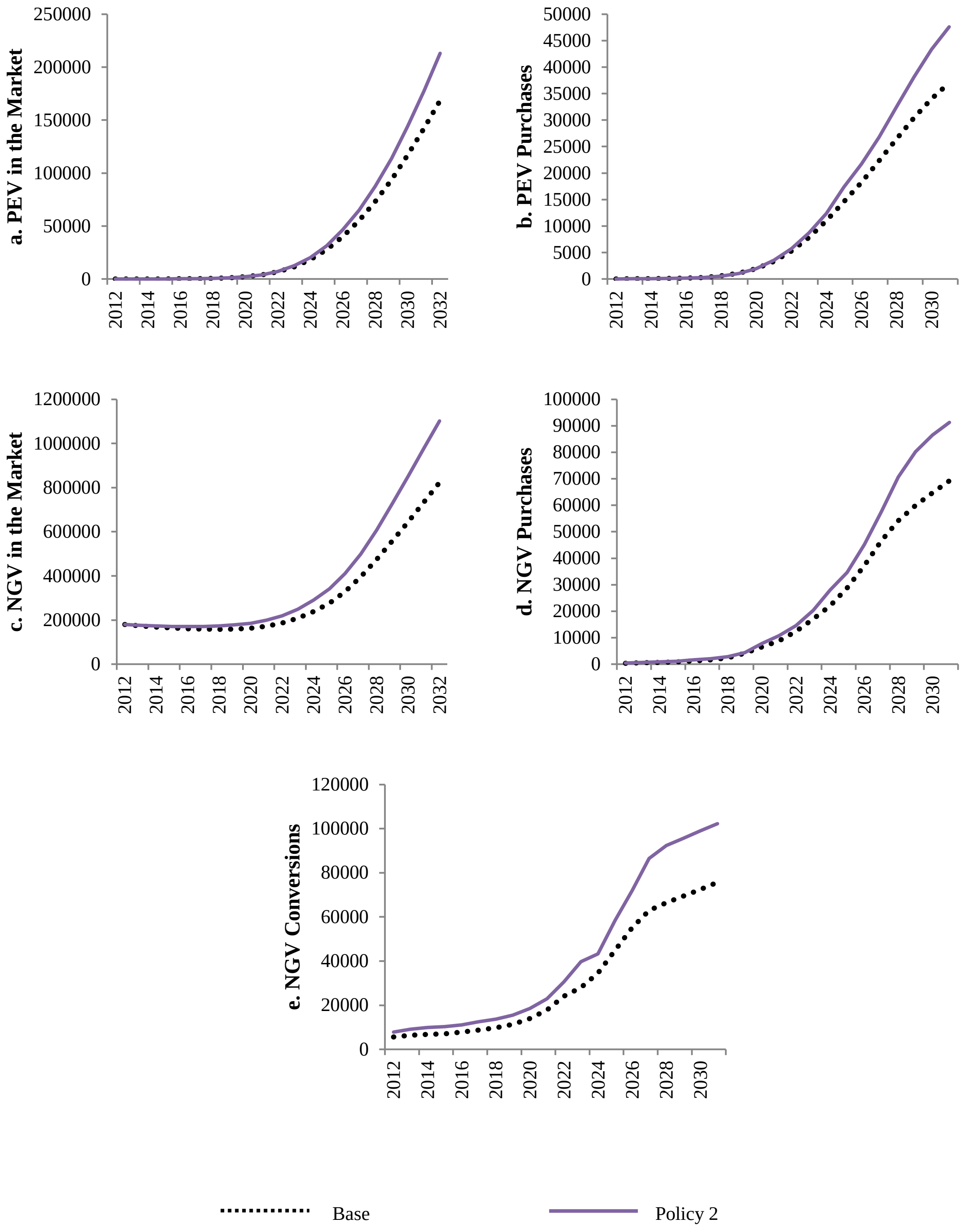

Fig. 6. Comparison between simulation results of Policy 2 and Base case. Figures shown, compared to the base case, the evolution over time of the variables: PEV market (Figure 6a), PEV purchases (Figure 6b), NGV market (Figure 6c), NGV purchases (Figure 6d), and NGV conversions (Figure 6e). The x-axis measures time since 2012. Y-axis units are vehicles. The continuous purple line represents the results of policy 2, and the dotted black line represents the base case results. Source: the authors, from simulation results.

Comparative analysis of the policies modeled

Table 4 provides the numerical summary of the number of vehicles of each technology in the three simulations carried out (Base, Policy 1, and Policy 2). In order to facilitate analysis of the results, on the left side of the table shows the percentage of market share for each technology in each simulation.

Table 4. Number of vehicles and market share

	Number of vehicles			**Market share**		
	Base	Policy 1	Policy 2	Base	Policy 1	Policy 2
Gasoline	3601198	3521785	3242461	78,4%	76,7%	71,1%
NGV	823800	894839	1101759	17,9%	19,5%	24,2%
PEV	168484	175930	212956	3,7%	3,8%	4,7%

Source: the authors, from simulation results.

In the base case, the percentage of market share at the end of the simulation was 78.4% for gasoline vehicles, 17.9% for NGV and 3.7% for PEV. This market share reflects a strong dominance of conventional vehicles over alternative fuel vehicles. Such dominance remained after applying the two policies. However, market shares were slightly modified. On one side, after apply the policy 1, the percentage of market share decreased by 2.2% for gasoline vehicles, while it increased by 8.6% for NGV and 4.4% for PEV. On the other side, after apply the policy 1, the percentage of market share decreased by 11% for gasoline vehicles, while it increased by 34.8% for NGV and 27.4% for PEV. This is a first indicator of the effectiveness of implemented policies and hints on the best performance of the policy 1 to encourage the adoption of alternative fuel vehicles.

A graphical summary of the results of simulated policies is shown in **Figure 7**. This figure allows do comparisons between the different curves obtained and noted several key elements in the found results.

Figures 7a and **7c** let us show that both strategies increased the number of AFVs in the market. .In all cases, the crucial time to takeoff of the diffusion was the year 2020. In the next five years, 2020-2025, the diffusion curves are very similar, apparently overlap each other. However, from 2026, the figures clearly show the differences in the paths associated with the policies studied. Communication policy encouraged more the adoption than fiscal policy.

When comparing the curves obtained for PEV purchases (**Figure 7b**), we can see that in the simulated time horizon purchases not fully describe the characteristic S-shaped diffusion process. By 2030, the spread of electric vehicles not yet reached the tipping point, which could mean more growth ahead.

For its part, the curves associated with the purchases and conversions of gas vehicles (**Figure 7c** and **d**) allow us to identify a tipping point around the year 2028. This behavior indicates either a possible saturation of this specific market or a decrease in the speed of such vehicles entering the Colombian market. Nevertheless, as shown in **Figure 6**, during the simulated time, NGV purchases always exceeded PEV purchases.

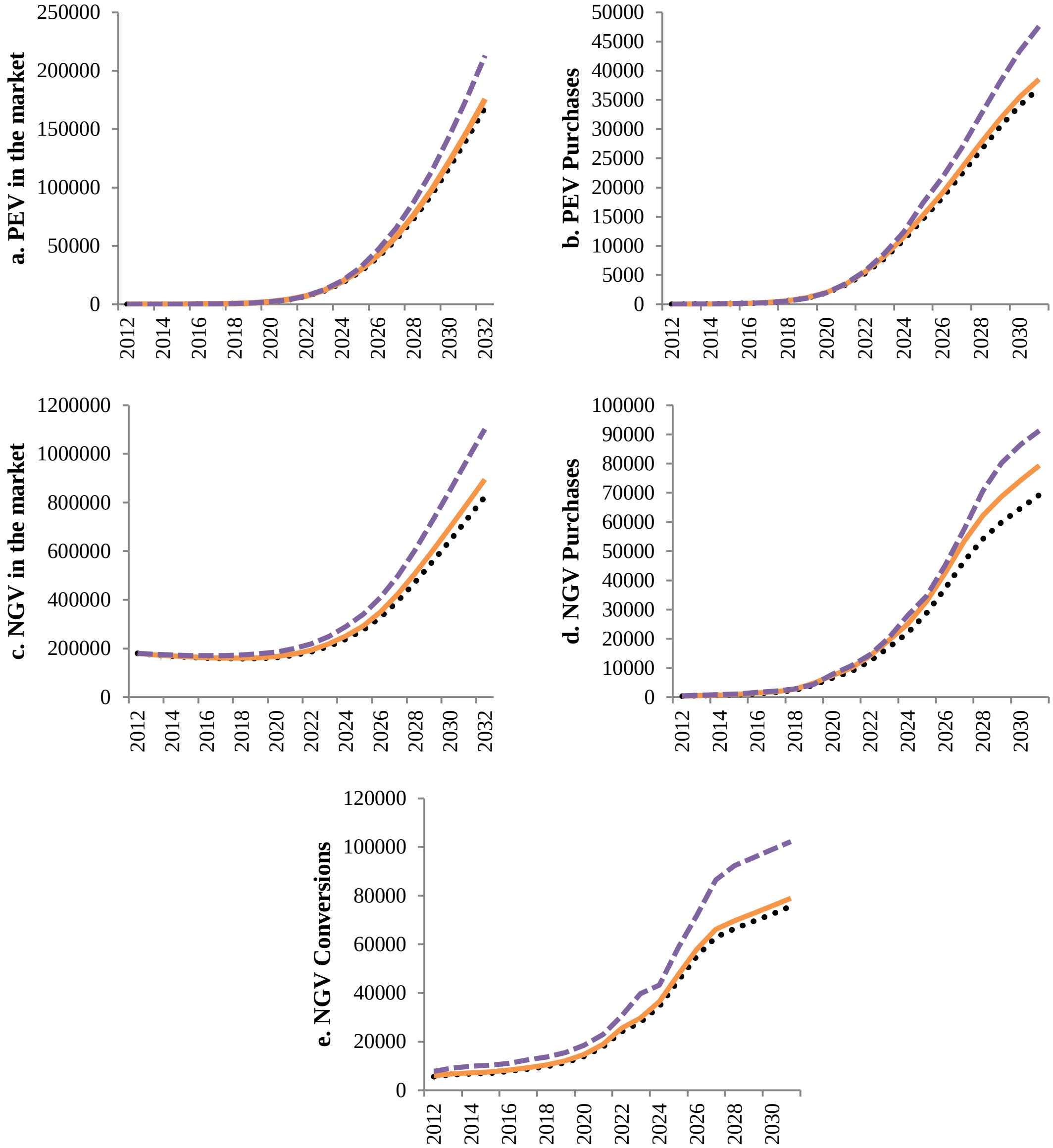

Fig. 7

Fig. 8. Comparison between simulation results of Policies and Base case. Figures shown, compared to the base case, the evolution over time of the variables: PEV market (Figure 7a), PEV purchases (Figure 7b), NGV market (Figure 7c), NGV purchases (Figure 7d), and NGV conversions (Figure 7e). The x-axis measures time since 2012. Y-axis units are vehicles. The continuous orange line represents the results of policy 1, the striped purple line represents of policy 2, and the dotted black line represents the base case results. Source: the authors, from simulation results.

Conclusions and summary

The conclusions of this research can be summarized in four statements in accordance with the objectives. Based on these statements, recommendations are proposed for stakeholders to promote a different model of mobility in the future through the adoption of alternative fuel vehicles.

1. *The AFV diffusion is affected by the traditional and consolidated automotive industry and the Colombian market characteristics.*

The design policy must consider market characteristics and background. In Colombia, the history of the diffusion of NGV offers a reference mode. It indicates some key aspects about the importance to develop strategies with public and private entities. In this way, the strategists can create effective incentives to respond to market signals.

2. *The obtained results evidence a slow diffusion of the technologies in the Colombian market.*

Under current conditions in the next 20 years, the Colombian market will remain dominated by traditional combustion vehicles and alternative fuel vehicles will have very little market share. This scenario poses challenges in the design, analysis and evaluation of strategies to promote adoption of alternative fuel vehicles. For example, the slow diffusion requires that policies are implemented for a long time in order to achieve self-sustaining levels of adoption.

3. *The results obtained from the simulation are consistent with these should be expected from the application of the bounded rationality theory.*

The model formulated using bounded rationality adequately explains the behavior of the studied phenomenon. Understanding the behavior can better analyze how the decision maker makes decisions and thereby develop better policies. Strategists should consider cognitive limitations of decision makers, in particular the difficulty of decision-makers to perform complex calculations, when develop strategies to stimulate the adoption of alternative fuel vehicles in order to increase the effectiveness of the measures.

4. *The results indicate that the communication policy is more effective than fiscal policy to promote a model of low-carbon private transport in the Colombian market.*

Results found indicate that the strategies designed to provide information to consumers to increase both knowledge and understanding of the technologies are more effective than tax reduction and regulatory changes. This result shows that to impulse the diffusion of AFVs in the Colombian market requires developing strategies that increase the consumer familiarity with the technologies and in consequence to promote a different model of mobility.

In summary, the results of the case study show that market penetration of AFVs will take a long time. These results indicate that promote the adoption of AFVs over others technologies in the market is a big challenge for the design of public policies and strategies.

Further analysis includes an empirical validation of the results. The validation should be made through experimentation with decision makers. In order to do this, a management simulator based on this simulation model can be used.

As a final point, although the model was developed for the Colombian case, the model can be extended to others developing economies with similar conditions after to calibrate adequately the model parameters.

Biographies

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Appendix A

Simulation data

The characteristics of the vehicles at the beginning of the simulation are presented in **Table 5**.

Tabla 5. Individual vehicle characteristics at the start of the simulation

Characteristic	Gasoline	NGV	PEV	Units
Autonomy	300	200	80	Km
Cost of conversion	0	3126000	160000000	pesos
Maintenance cost	1000000	700000	0	pesos
Operational cost	7467	4406	2012	pesos
Emissions	200	130	0	TonC/vehicles
Price	35906000	39856000	80257000	pesos
Supply stations	3500	840	5	stations
Supply time	600	900	10000	s