# LIFE CYCLE ASSESSMENT FOR CONVENTIONAL VEHICLE, ELECTRIC VEHICLE AND PLUG-IN ELECTRIC VEHICLE FOR BRAZILIAN CONDITIONS

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*Abstract. Studies for electric and hybrid vehicles has attracted the attention of manufacturers, governments and consumers, mainly due to problems related with the increase in emissions of greenhouse gases, such as increasing global warming, climate change and health problems in people who are exposed to this pollution.This work is carried out an environmental comparison between conventional vehicle, electric vehicle and hybrid vehicle plug-in through an approach of Life Cycle Analysis (LCA). The methodological tool used was the Life Cycle Assessment (LCA) Well-to-Wheel fuel and electricity, as well as LCA of the vehicle. The environmental assessment was performed using the SimaPro 7.0.1 software and CML 2 baseline methodology in 2000, developed by the Institute of Environmental Sciences (CML). The common basis of analysis undertaken in this study was 1 km traveled. The analysis of the results shows that scenarios using ethanol as part of the fuel, have the biggest environmental impact for categories: eutrophication. Systems using gasoline as part of the fuel, have the greatest potential impact on global warming. Systems using lithium-ion battery have the biggest impact on human toxicity.*

*Keywords: LCA, conventional vehicle, electric vehicle, plug in electric vehicle.*

## 1. NOMENCLATURE

$CO_2$ - carbon dioxide
HC - hydrocarbons
SOx - sulfur oxides
CO - carbon monoxide
NOx - nitrogen oxides
LCA - Life Cycle Assessment
ICEVg - internal combustion engine vehicle that uses gasoline as an energy source
BEV - electric vehicle powered by electricity

PHEV - hybrid vehicle plug-in gasoline and electric powered
GWP - Global Warming Potential
Eq - equivalent
$SO_2$ - Sulfur dioxide
1,4 DB - 1.4 Dichlorobenzene
ED - Only electricity
GD - Only gasoline
MD – mixed units

## 2. INTRODUCTION

In developing countries like India, China and Brazil, the annual growth in car fleet increases rapidly, as well as environmental emissions linked to transport. In these countries, the public transport is insufficient, vehicle management is deficient, besides technology vehicle being obsolete. To further aggravate the situation, non-motorized transport is being replaced by motor vehicles, due to increased income of the population (Ximenes et al., 2010).

According MME (2011), the transportation sector in Brazil is the second largest user of final energy, between 25 and 30% of total energy use in the country. Furthermore, this sector still accounts for 55% of the oil consumed in Brazil. However, when compared to the world average, the consumption of fossil fuels in Brazil's Transport sector is lower, due to the addition of 25% ethanol to gasoline and the large number of vehicles using hydrous ethanol as a fuel. However, even under these conditions, the combustion process emits gases such as carbon dioxide ($CO_2$), hydrocarbons (HC), sulfur oxides (SOx), carbon monoxide (CO) and nitrogen oxides (NOx), and others still. These greenhouse gases lead to many harmful situations to the environment, such as the intensification of the greenhouse effect, climate change, acidification of soil and water resources, onset of respiratory and cancer problems in people who are exposed to these emissions (Momoh and Omoigui, 2009).

According Balat et al. (2008), much of the current effort to control greenhouse gas emissions and the search for sustainability in the automotive sector, focuses on:

- Reduce energy consumption,
- Increase the conversion efficiency or the use of energy,
- Use of alternative fuels, especially renewable fuels;
- Develop more efficient engines,

- Promote technological progress in order to implement new propulsion systems,
- Introduce measures to control and minimize the traffic,
- Incite new driving behavior;
- Promote capture and storage of $CO_2$.

Therefore, there are numerous ways to transform the energy and emissions systems. To occur this, it is required large investments, combined with supporting policies, which are fundamental to implement and finance the move. The investment can be found through the national and local policies and institutional mechanisms, which are also able to support the effective changes. Given this need for change, there is a technique to analyze the entire chain of production, use and end of life processes and products, considering the energy resources, raw materials and emissions from these activities. This method is the Life Cycle Assessment (LCA). This work applies LCA for different scenarios of vehicle technology/fuel in Brazil, in order find out the environmental impacts caused by each of these systems, and from these results, perform comparisons of the systems under study.

Finally, it is justified to carry out this work, on the need for appropriate studies that generate relevant information and evidence the potential environmental impacts of automotive systems, so that can be developed tools that can assist in making decisions related to the improvement of social conditions and reductions of environmental impacts.

## 3. METHODOLOGY

LCA is a tool used to evaluate environmental and energy aspects associated with product and processes during the entire life cycle, from cradle to grave. Figure 1 shows the typical stages of life cycle of products (Rubin, 2001).
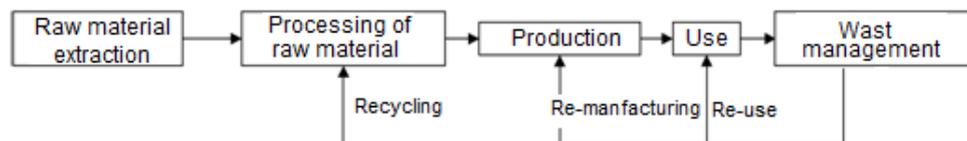


Figure 1. Life Cycle steps.

The process for analyzing the life cycle comprehend a methodological framework internationally standardized by ISO, in which are determined the phases and the general procedures of executing a LCA study, comprising the following steps: I- Objectives and scope of the study, II- Life cycle inventory , III- Life cycle impact assessment and IV- Result interpretation (Finkbeiner et al., 2006).

To evaluate the environmental impacts associated with passenger vehicles requires consideration of their complete life cycles, since the production of raw materials, not only in vehicle use, but also in their production and fuel supply chains. The distribution of these charges will be very different depending on powertrain technologies and fuel production routes (Bauer et al., 2015).

### 3.1 Objective and scope of the study

The proposal of this study is to perform an assessment of the environmental impacts of the following vehicle/fuel systems: internal combustion engine vehicle that uses gasoline as an energy source (ICEVg); electric vehicle powered by electricity (BEV); hybrid vehicle plug-in gasoline and electric powered (PHEV) in Brazilian conditions through the application of LCA.

*3.1.1 System function*:
Use of a means of transport to produce displacement of a passenger per kilometer.
*3.1.2 Functional unit*:
Distance of 1km of a passenger in a car.
*3.1.3 System boundaries:*
The following are three scenarios in this study, which were chosen different energy sources and propulsion system.

a) System boundaries for Scenario 1: ICEVg
The first scenario is composed of an internal combustion engine vehicle that uses gasoline as fuel. The proportions defined by current legislation in Brazil, it is assumed that the gasoline sold to the final consumer is a mixture in the ratio of 75% gasoline, 25% ethanol. Figure 2 shows the system boundaries for this first scenario.
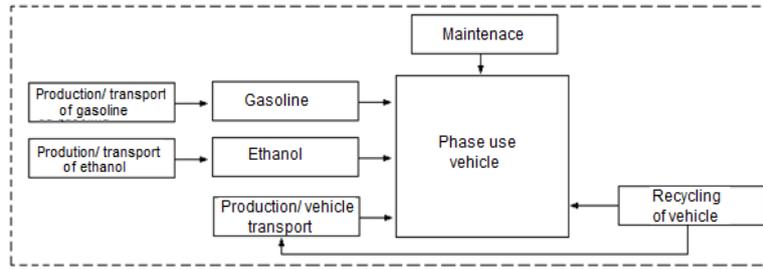
Figure 2. Border system for ICEVg.

b) System boundaries for Scenario 2: PHEV

The second scenario is composed of an electric motor and a support motor, which in this case is the internal combustion. This type of car travels part of the way in electric mode, in which air emissions are nil, and specific parts with the internal combustion engine system (ABVE, 2009). Figure 3 shows the system boundaries for this first scenario.
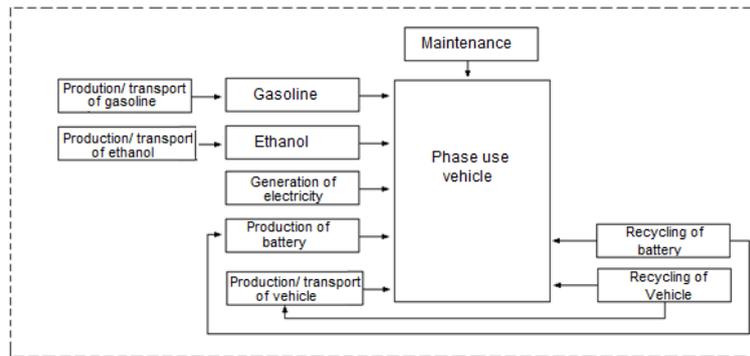


Figure 3. Border system for PHEV.

c) System boundaries for Scenario 3: BEV

This type of car used as propulsion electric motor, an energy storage system, battery, and the power source, electricity. Figure 4 shows the boundaries for this scenario.
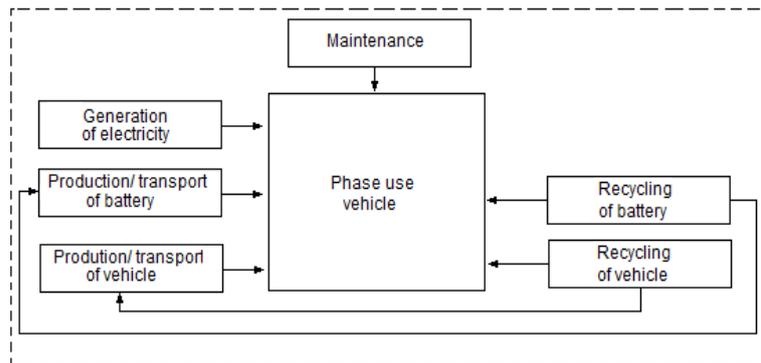


Figure 4. Border system for BEV.

**3.2 Life Cycle Inventory – Data collect**

The Life Cycle Inventory stage, according to ISO14040 (2006), involves the collection of data and the procedures used to quantify the inputs (materials and energy) and outputs (as atmospheric emissions, liquid effluents and solid waste ) throughout the life cycle of product.

### 3.2.1 Gasoline

The steps included in the inventory of gasoline were: petroleum extraction and transportation, refining, gas transport and use. This includes pre-production, current production of the final product, but were not included the production machines used for this functionality. It was considered the Borges, (2004) study data, in which it determined that the oil used for the production of gasoline in Brazil has two distinct origins, and set the value of 50% of the oil from sources international, and 50% of oil from domestic basins.

### 3.2.2 Ethanol

The steps included in the inventory of ethanol were: agriculture, transport, ethanol production, and end use. The data used in ethanol inventories were collected data from literature, Cavalett et al., (2012).

### 3.2.3 Electricity

To determine the impact of the production and use of energy on the environment is necessary to approach different energy conversion processes that integrate the Brazilian energy matrix, which are associated with the following processes: hydro, conventional thermal power, nuclear power, energy wind (Miranda, et al., 2012). The data used for electricity inventories were collected from Ecoinvent database.

### 3.2.4 Conventional vehicle (with internal combustion engine)

The inventory of the Golf vehicle was used for this study. The data were adapted to model their specific characteristics, especially the data related to the body and other parts that are common to the family car segment. Thus this inventory was used for all vehicles in the study, and the main specific features for PHEV and BEV as the battery, the specific consumption and range of each vehicle, they were collected from other specific sources.

The data used for the inventory automobile life cycle have been adapted from the study Schweimer et al., (2001), which had reference to the production plant of Volkswagen in Germany.

### 3.2.5 Lithium ion battery for PHEV and BEV

In order to make a comparison with the focus on production and use battery for electric vehicles, it was decided to keep the inventory of conventional car, adding the life cycle of a lithium ion battery.

According to consulted references and to simplify inventories, it was considered the same battery representative of both the PHEV technology as BEV. In practice, the state of the art these batteries have electrochemical properties and materials slightly different, however, Gaines et al., (2000), Schexnayder et al., (2001), and Ying et al., (2006), combined the inventory in order to achieve a representative general inventory for both technologies. The data for this study were adapted from Majeau-Bettez et al., (2011).

### 3.2.6 End use

The distance adopted for the end use of the vehicles in the study was based on the average useful life of a car in Brazil, 160,000km (FENABRAVE, 2011).

The mixture of gasoline and ethanol is used for two different scenarios: ICEVg and PHEV. In order to obtain the data necessary for consumption of the motor, it is necessary to know the consumption (km / l) of the vehicle and the proportions of the fuel used. Table 6 shows the data used for inventories of ICEVg use.

Table 1. ICEVg use.

| ICEVg | Amount |
|---|---|
| Lifetime (km) | 160000 |
| Consumption (km/l) | 12,2 |
| Total gasoline (l) | 9836,1 |
| Total ethanol (l) | 3278,7 |

The end use for the BEV and the electrical portion of the PHEV is the mechanism for charging and discharging the battery. This magnitude is directly linked to the distance traveled by the vehicle and losses. All data related to operation of power consumption of the electric vehicle and additional losses were estimated in existing vehicles and theoretical considerations (Faria et al., 2013). Table 7 shows the consumption data for the PHEV (Volt) and BEV (Leaf) used in this work, which were obtained by the sites of the automotive industry Nissan Portugal and Chevrolet United States.

Table 2. PHEV and BEV use.

| Vehicles Features | PHEV | BEV |
|---|---:|---:|
| Battery weight (kg) | 197 | 300 |
| Vehicle weight (kg) | 1715 | 1521 |
| Range (km) | 580 (80ED + 500ER) | 160 |
| Electricity consumption (kWh / 100 km) | 17 | 17 |
| Gasoline consumption (l / 100 km) | 0(ED) 6.9(GD) 3.9(MD) | 0 |
| Distance by electricity (km) | 22400,0 | 160000 |
| Distance by gasoline (km) | 137600 | 0 |
| Electricity consumption (kWh) | 3808 | 27200 |
| Gasoline consumption  in lifetime(l) | 7120,8 | 0 |
| Ethanol consumption in lifetime (l) | 2373,6 | 0 |

**3.3 Life cycle impact assessment**

This step is performed with the support of SimaPro software, developed by Pre-Consultants. This program is used in order to analyze, identify and compare the environmental impacts of the scenarios analyzed. The impact categories chosen for this study were: Global Warming Potential, Human Toxicity, Acidification.

**4. RESULTS**

This stage presents the potential environmental impacts of the three scenarios studied

**4.1 Global Warming Potential (GWP)**

As shown in Figure 5 the ICEVg has the biggest impact for the GWP, with the emission of 2,29E-01 kg of $CO_2$ eq./km. This is due to the large amount of $CO_2$ emitted into the atmosphere from the combustion of gasoline. This ratio is lower than the world average, mainly due to the addition of anhydrous ethanol to the composition of gasoline. Production of vehicle to ICEVg is responsible for about 25% of the total emission of $CO_2$ eq, which has the largest contributor to the steps of processing of materials and manufacturing. The production of fuel is responsible for 14% of $CO_2$ equivalent emissions. Exhaust emissions account for approximately 60% of total $CO_2$ eq, and recycling of vehicle by -4.0%.

The PHEV has the second highest result for the GWP, with the value of 1,84E-01 kg of $CO_2$ eq./km. This result varies according to the energy matrix considered and the specific amounts of gasoline and electricity adopted, in this case the exhaust emission in electric mode corresponds to only 7.5% of the total travelled distance.

With the result of 1,18E-01 kg of $CO_2$ eq./km, the best result was for the BEV, which has a characteristic zero exhaust emission. A key factor for this result was the use of data relating to the Brazilian energy matrix, which has a renewable energy base and a consequently lower emission of greenhouse gases in the energy production stage. The Production of battery corresponds to 35% of $CO_2$ eq emissions. The production of vehicle is responsible for about 50% of total emission, while production o fuel by approximately 15%, recycling of automobile is responsible for about -5.5% and recycling of the battery by -3.5% of $CO_2$ eq emissions.
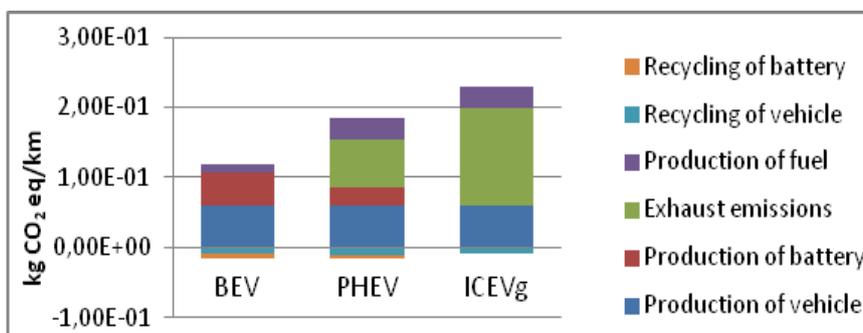


Figure 5. Global Warming Potential.

## 4.2 Acidification Potential

According to Figure 6, the ICEVg has the biggest potential for acidification, with 5,86E- 04 kg $SO_2$ eq./ km. The most responsible for this result is the anhydrous ethanol added to the gasoline. The production of fuel contributes approximately 72% of the emissions. The production of vehicle is responsible for about 20%, exhaust emissions by 8% and recycling of vehicle by -4% of $SO_2$ emissions eq.

The second potential is higher for the PHEV with the result 5,19E-04 kg $SO_2$ eq./km. The use of electricity from renewable sources benefits the result for this category of impact. The production of vehicle is responsible for about 24% of production of fuel with 66%, the exhaust emissions by 6%, the production of battery 4%, recycling of vehicle -4% and recycling of battery by -1% of $SO_2$ emissions eq.

The best result was for BEV, with 3,03E-04 kg $SO_2$ eq./km. The production of battery 10% of total contribution of $SO_2$ eq. Production of vehicle is responsible for about 39% to production of fuel contributes 49%, exhaust emissions by 6%, and recycling of vehicle is responsible for -8% and the recycling of battery for -2% of emissions $SO_2$ eq.
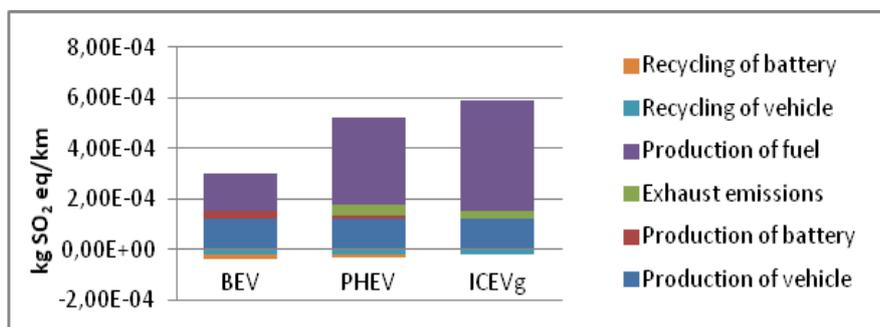


Figure 6. Acidification Potential.

## 4.3 Human toxicity potential

According to Figure 7 the biggest human toxicity potential is for BEV with 7,04E-02 kg 1,4-DB eq / km. The production of battery has the most significant contribution to this impact category, with 57% of the total contribution of 1,4-DB eq. This result is mainly due to the high charges of toxic substances that are released by mining activities metals (such as nickel, copper, platinum and aluminum). The production of vehicle is responsible for approximately 37%, electricity production contributes only 6%, recycling of vehicle with -5% and recycling of battery emissions by -6% 1,4-DB.

The PHEV has the second highest result for human toxicity 6,38E-02 kg 1,4-DB eq / km. The production of battery is responsible for 30%, production of vehicle is responsible for 40%, the production of fuel corresponding to 29% recycling of the vehicle is responsible for -6.5% and recycling of battery for -4% of emissions of 1,4-DB.

The best result for human toxicity potential is to ICEVg with the value of 4,30E-02 kg 1,4-DB eq / km. The production vehicle is responsible for approximately 60% of emissions. The production of fuel corresponds to 38% of impacts on human toxicity. Recycling of vehicle is responsible for -8%.
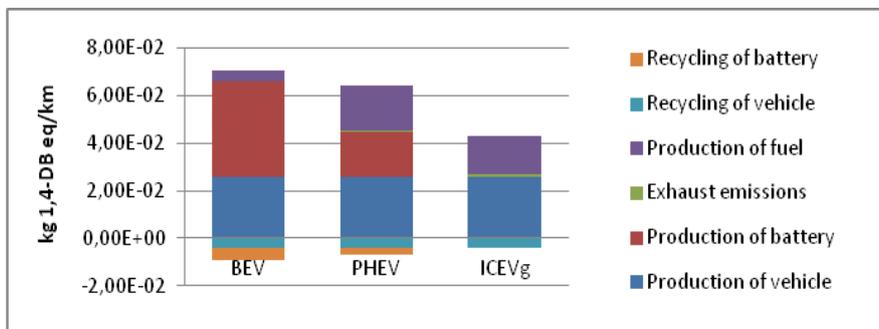


Figure 7. Human toxicity potential.

**4.4 General comparison between vehicles**

In general, there is no technology with best performance in all types of impact. However, according to Fig. 8, from a single indicator which would be calculated using the area of each vehicle system, the smaller relative value would be for the BEV. For the poles having the acidification and global warming categories, the highest values are for vehicles that use gasoline as part of its fuel. For the edge featuring the category of human toxicity, the highest values are for vehicles that have a lithium-ion battery.
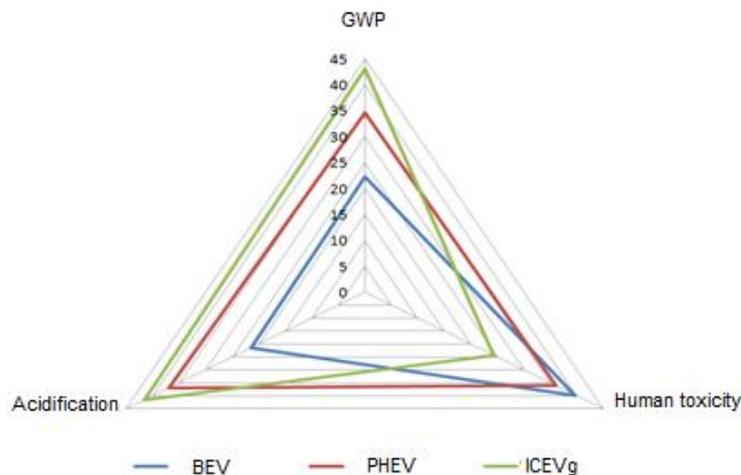


Figure 8. Human toxicity potential

**5. CONCLUSIONS**

Environmental impacts quantified from the application of LCA to study were: global warming, eutrophication and human toxicity, and these can be used as an auxiliary tool in decision making aimed at the search for sustainability. However, for an accurate conclusion about which automotive system is best suited for use, one must perform a holistic research regarding the production and use of automobiles, and other parameters should also be investigated as, for example, energy efficiency, land use, costs, availability of materials in nature, distribution network, logistics energy sources, government strategies, among others.

To global warming, the ICEVg has the biggest potential impact, the PHEV has a potential 20% lower and the BEV, approximately 50% lower than the ICEVg.

To the category human toxicity, the BEV has the biggest potential impact, the PHEV has a potential 10% and ICEVg approximately 40% lower than the BEV.

To the category of acidification, ICEVg has the biggest potential impact, the PHEV has a potential 10% lower and the BEV approximately 50% lower than the ICEVg.

In general, PHEV has characteristics similar to ICEVg, because it also uses gasoline as fuel, but due to the use of electricity, the result for the global warming potential and acidification are smaller than the IVECg. PHEV also presents similar features the BEV for making the use of electricity and lithium ion, it resulting higher results for the for human toxicity potential.

**6. ACKNOWLEDGEMENTS**

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