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Comparative LCA of electric, hybrid, LPG, diesel and gasoline cars in Belgian context

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Abstract

In this paper, an environmental comparison of electric, hybrid, LPG, diesel and gasoline passenger vehicles is performed through a Life Cycle Assessment (LCA) approach. Thanks to a range-based modeling system, the variations of the weight, the fuel consumption and the emissions within the family car category are considered instead of the average values. Unlike in a classic LCA, the use phase of vehicles has been modeled to cover vehicles with both a short and long lifespan in such way that the number of times a vehicle needs to be produced to cover the comparison basis or functional unit is taken into account.

According to the assumptions and the used impact calculation method, the greenhouse effect of the LPG hybrid and battery electric vehicles are respectively 20.27 %, 27.44 % and 72.56% lower than for the gasoline vehicles. The assessment of the impact on human health and the air acidification give the best environmental score to the battery electric vehicle. A sensitivity analysis has allowed the assessment of the correlation between the respiratory effects and the euro emission standards.

Keywords: LCA, BEV, HEV, LPG, Gasoline engine

1 Introduction

When performing automotive LCA at country or community level, LCA practitioners are facing with two main problems. How to collect , manage and treat the big amounts of data on one hand and how to produce LCA results reflecting all the differences between the cars in term of segment, technology, drivetrains, fuels, weight and emission standards on the other hand. The classic modeling approach of an LCA allows using single values for each parameter of the model. In such an approach, a new model should be developed for each specific type of cars and modified for each change of a value of a parameter. The complete assessment of all the type of cars of a given fleet would obviously be time consuming and would require a big amount of resources.

Furthermore, producing individual LCA results for each specific car of a fleet will make the management and the utilization of these results inefficient with a high likeliness of errors which increases with the number of results.

The range based-modeling system is an innovative LCA approach allowing the use of range of values, instead of average ones, with respect for their statistical distribution. Thanks to this approach, different vehicles with different technologies and fuels could be assessed in one single model. In this paper, the complete LCA of electric, hybrid, LPG, diesel and gasoline cars have been performed with the range-based modeling system and with respect to different impact categories.

2 Methodology

Life Cycle Assessment (LCA) is a standardized methodology [1,2] which studies the environmental aspects and potential impacts of a product/service from ‘cradle-to-grave’ i.e. from raw material acquisition through production and use until disposal. When performing an LCA, one should first define the goal and the scope of the study including the geographical and temporal limitations. After completing this step, all the inputs (materials and energy) and outputs (emissions) involved in the studied product system are computed with respect to the Functional Unit (F.U) which is the quantified reference performance of the product/service. The input and output data are then converted into their corresponding environmental impacts. Finally, the environmental impacts are interpreted in order to localize the sources of the most relevant impacts and to find an improvement opportunity of the ecological quality of the product/service.

2.1 Range-based LCA

The different vehicle technologies are modeled in one single LCA tree (Figure 1). For each specific vehicle technology, the fuel consumption, the weight, and the different emissions are written as statistical distributions. The data analysis methodology described in the paragraph 3.2 has allowed attributing to each range of data the most relevant distribution. A preliminary calculation has showed that the fuel consumption is the most important parameter of the model and it has almost a perfect correlation with the greenhouse effect which is one the of the most important impact category in LCA of vehicles. So, it has been decided to write the distribution of all the other parameters (weight and emissions) in function of the distribution of the fuel consumption. As a consequence, when running the LCA model, all the parameters will vary in function of the variation of the fuel consumption instead of varying independently. This will create a dynamic model in which every change in one part of the model will influence the other parts allowing a permanent and automatic sensitivity analysis.

3 Assumptions

In this study, the vehicle technologies which are assessed belong to the family car segment. It includes all the type of vehicles registered in Belgium within this segment. For each specific technology, the ranges of the weights, the emissions and the fuel consumption instead of average values are taken into account in the assessment. The ranges of data are extracted from the Ecoscore database [3] which includes all the type of cars available in the Belgian fleet. A special attention has been dedicated to the LPG, hybrid and Battery Electric Vehicle (BEV). Since the LCI data of the LPG don’t exist in the Ecoinvent database [4], the feedstock input and the energy consumption during the different steps of its production (Tables 1 and 2) have been gathered from the CONCAWE report [5] and used in the LCA model.

Table 1: Energy consumption during the liquefaction and the distribution of 1 GJ of LPG [5].

Processes	energy consumption (MJ/GJ of LPG)
Liquefaction	10
Distribution	20
Compression	10

Table 2: Main inputs for the production of 1liter of LPG [6, 5].

Inputs	amount
Propane/butane	0.55 kg
Natural gas burned in gas motor	1.01 MJ

The only BEV which is registered in Belgium as a family car is the Tesla Roadster. During the modeling of the manufacturing step of this car, the specifications of the battery (Table 3) as well as its material breakdown have been included.

Table 3: Specifications of the Lithium-ion battery of the Tesla Roadster [7]

Technology	Lithium-ion
Weight	450 kg
Range	354 km
Lifetime	160934 km
Number of the units for the F.U	2

However, the LCI data of the electrolyte of the lithium-ion battery which is the lithium hexafluoro phosphate (LiPF6) was not available in the Ecoinvent database [4]. To solve this problem, the electrolyte has been modeled on the basis of its chemical synthesis with respect to industrial production requirements in terms of materials, energy, and catalysts (Table 4).

$$PCl_5 + 6LiF \rightarrow 5LiCl + LiPF6 \qquad (1)$$

Table 4: Manufacturing data of 1 kg of LiPF6 [8]

LiF6	0.2 kg
PCl5	1.7 kg
CaF2	4.4 kg
H2SO4	5.8 kg
Electricity	23.6 kWh
Fuel oil	0.44 MJ

Hybrid car has been assumed to be equipped with nickel metal hydride (NiMH) battery ranging from 50 kg to 57 kg [9], has been considered. The material breakdown, the assembly energy and the chemistry of the electrolyte of the battery have been used to model the NiMH battery.

3.1 Manufacturing and End-of-life

The manufacturing step has been modeled as common parameter for all the vehicle technologies with respect to their weight. It includes the raw materials, the manufacturing processes, the energy consumption and the transport by rail and truck of the manufactured car to the end-user. However, the components which are specific to the type of the technology are modeled separately (NiMH and Lithium batteries).

The end-of-life has been modeled with respect to the state-of-the art in Belgian recycling plants [10]. The global recycling rate of vehicles and consumption of resources during the recycling process have been included, as well as the range of recycling rates per type of material (Table 5). The efficiency of recycling processes and the real capacity of recycling plants were taken into account as well. Like for the manufacturing phase, the end-of-life phase has been modeled as a parameter which will be adapted to all the vehicles according to their weight. An energy consumption of 66kWh/ton [11] is considered for the shredding and the further separation processes.

Table 5: Recovery rates of end-of -life vehicle materials [10]

Material	Average recycling rate (%)	Average energetic valorization rate (%)	Total recovery rate (%)
Ferro-metals	99.82	0.00	99.82
Aluminum	93.20	0.00	93.20
Copper	88.53	0.00	88.53
Zinc	93.49	0.00	93.49
Lead	91.43	0.00	91.43
Polypropylene	51.99	2.47	54.47
Polyethylene	51.99	2.47	54.47
PMMA	3.00	29.49	32.49
ABS	49.27	4.95	54.21
PET	0.73	35.53	36.26
EPP	2.93	0.01	2.94
PP-EPDM	5.55	2.47	8.02
Polyurethane	5.58	1.03	6.61
Rubber	3.47	28.56	32.03
Textile	6.19	2.10	8.29

PMMA: poly(methyl methacrylate), ABS: Acrylonitrile Butadiene Styrene, ,PET: Polyethylene terephthalate, EPP: Expanded Polypropylene , PP-EPDM: Polypropylene-Ethylene Propylene Diene M-class rubber

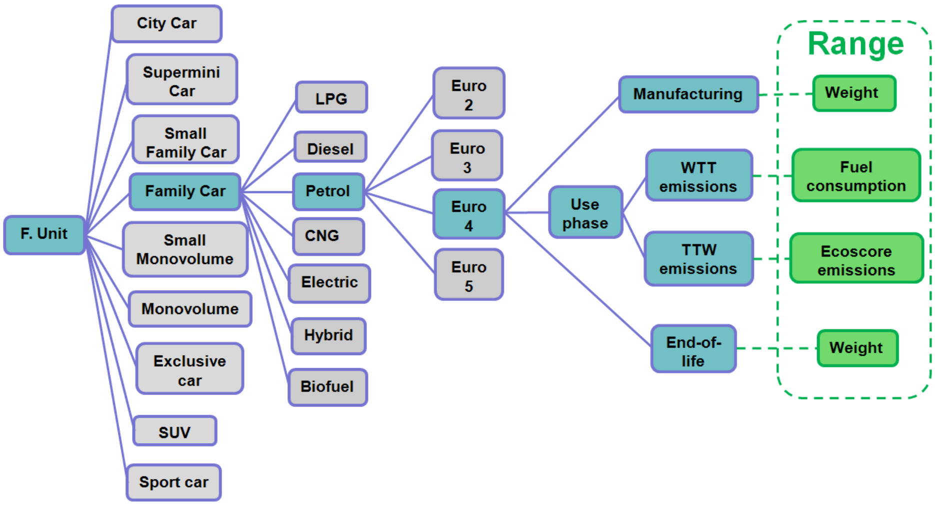

Figure 1: Range-based modeling system

3.2 Direct emissions and data analysis

The modeling parameters of the life cycle of the different vehicles are extracted from the Ecoscore database [3]. A data analysis was performed, to extract these parameters from the raw data available in the Ecoscore database [3]. Since the Belgian fleet includes a big variety of cars, the modeling parameters are not fixed values but ranges. In the model all the possible variations of these parameters are taken into account, resulting in a variation of the considered impacts. When including the frequencies of these values, one can match a triangular or uniform distribution with the real distribution of the values. Figure 2 and Figure 3 give an example of this approach for a euro 4 family car driving on petrol.

There are strong correlations between fuel consumption and weight, carbon dioxide and sulphur dioxide. These parameters can be described as a linear function of fuel consumption, multiplied with an 'error' distribution, expressing the difference between the linear equation and the real distribution of the parameter. For the other emissions (HC, NO_x, CO, PM, CH_4 and N_2O), no satisfying correlation was found. These emissions are modeled as a triangular or a uniform distribution, matching the reality as closely as possible.

The chosen distributions have an important impact on the overall result, preliminary conclusions of the data analysis are therefore interesting to discuss.

Fuel, weight, carbon dioxide and sulphur dioxide are highly dependent of the chosen segment. On the opposite, the euro standard does not influence these parameters. Impacts of manufacturing and well-to-tank emissions do not change by introducing newer euro standards. Tank-to-wheel emissions of carbon dioxide and sulphur dioxide will also not change by introducing newer euro standards. On the other hand it is noticeable that the euro standard influences highly the other regulated tank to wheel emissions. The higher the euro standard, the lower HC, NO_x, CO, PM, CH_4 and N_2O emissions are.

Next to the homologation emissions provided in the Ecoscore database, heavy metals and non-exhaust emissions have been included in the LCA model. In one hand, the heavy metals, expressed in milligram per kg of burned fuel, are gathered from the CORINAIR project [12]. In the other hand, the particulate matter emissions produced by the abrasion of the tires and the brakes are collected from [12] as well and included in the LCA model. Consequently, both tailpipe and non-exhaust emissions and their effect on the environment are taken into account in this study.

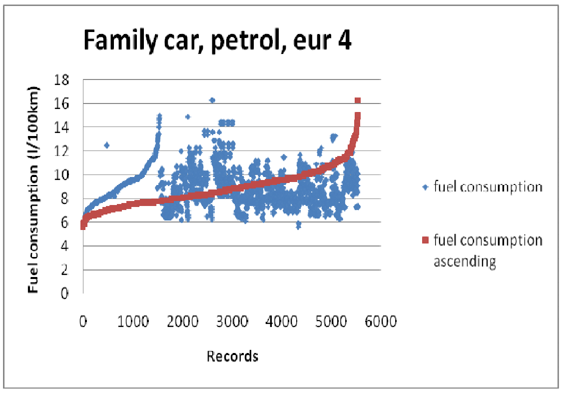

Figure 2: Range of the fuel consumption of the family petrol euro 4 car

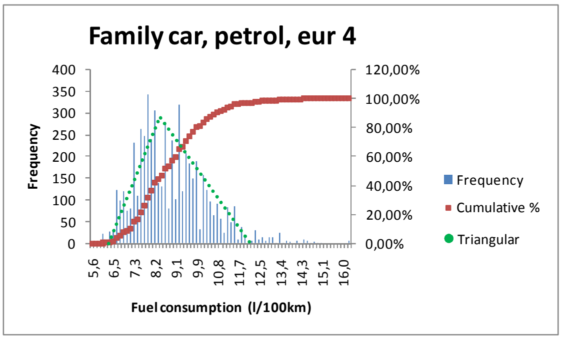

Figure 3: Distribution of the fuel consumption of the family petrol euro 4 car

3.3 The Functional Unit (F.U) and the real lifetime driven distance

To compare the environmental impact of the different vehicle technologies, a F.U has been defined. It corresponds to the use of a passenger car in Belgium during 13.7 years and a lifetime driven distance of 230500 km. As a car can have a lifetime driven distance shorter or longer than the F.U, the actual lifetime driven distance has been modeled with a normal distribution covering about 50000 km to more than 400000 km with an average corresponding to the F.U. The multiplication of the manufacturing step of a vehicle by the quotient of the F.U over the effectively driven distance will allow taking into account the number of time a vehicle will need to be produced to correspond to the F.U. When calculating the LCA results, a driven distance is chosen randomly between the minimum and the maximum of the normal distribution of the effectively driven distance. For each calculation, 1000 iterations producing 1000 results are performed in order to include all the possible situations in the assessment.

4 Results

LCA results are functions of the environmental impact calculation methods. It is important to understand and interpret all of the individual results in the context of the chosen calculation method.

In this study, three calculation methods have been used:

- The Greenhouse Effect 2007 (100 years)
- Human Health [13]
- Air Acidification

One can notice in the Figure 4 that the ranking of the vehicles are different according to the considered impact categories. When dealing with the Greenhouse Effect (GHE), gasoline cars have a big impact compared to the others. This is due essentially to the released emissions during the combustion of the gasoline. It is followed by the LPG car because of the combustion emissions of the LPG made with a propane and butane. Thanks to the contribution of the NiMH battery, the gasoline consumption of the hybrid car has been reduced and as a consequence its GHE is lower compared to other Internal Combustion Engines (ICE) vehicles. The BEV has the lowest GHE because it has zero tailpipe emissions. This is also the case when including the production and the distribution of the electricity which are not greenhouse emission free.

The calculation of the air acidification (Figure 4) has revealed that the gasoline, followed by the diesel car, is again contributing more than the other technologies. One can notice that the hybrid and the LPG cars have almost the same acidification impact with a minor advantage for the hybrid one. This is due to the production of the nickel used in the hybrid car NiMH battery. The production of nickel is responsible for a higher emission of nitrogen oxides and sulphur oxides which are the main pollutants leading the acidification process. The emissions of the same pollutants during gasoline production explain the results of the gasoline and LPG cars. Again for this impact category, the BEV scores better.

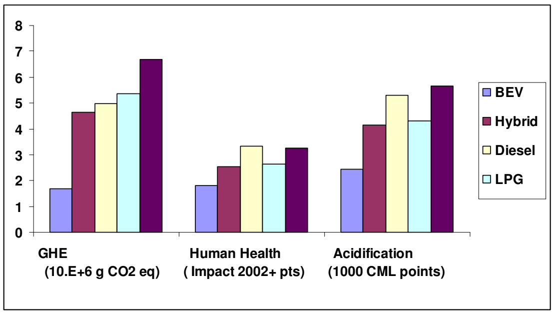

Figure 4: Comparative results of BEV, Hybrid, LPG, Diesel and Gasoline cars

The assessment of the different life cycle steps of the different vehicles (Figure 5) shows that the use phase is the main cause of the GHE for all the analyzed vehicle technologies. In the specific case of gasoline cars, moving to recent euro standard cars (euro 4 and 5) does not reduce their GHE. In the case of LPG cars, euro 4 cars seem to contribute slightly more to the GHE compared to euro 2 and 3 vehicles. This is probably due to the fact that new cars are becoming heavier because of extra options.

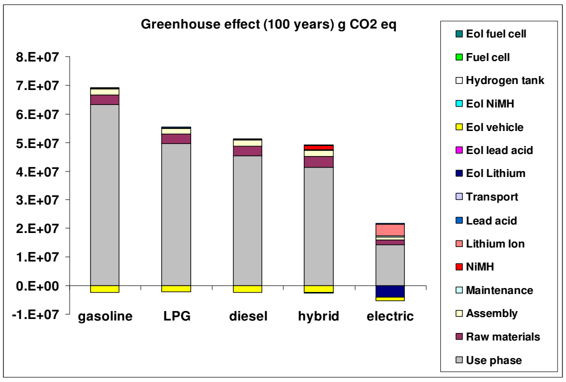

Figure 5: Contribution of the different life cycle steps to the GHE

The calculation of the human health impact (Figure 6) with the Impact 2002 + tool [13] confirmed the ranking given by the air acidification assessment. This is due to the fact that the Nitrogen oxides and sulphur oxides are pollutants with high contribution for both air acidification and human health. The BEV scores again better than the other technologies for this impact category. In order to have a clear comprehension of this result, the different vehicle technologies have been compared to each other at all the life cycle steps. The comparison revealed that the use phase is the main responsible of this impact for all the technologies. The step by step comparison showed that the hybrid car has a relatively high impact for the manufacturing phase (raw material and assembly). For the battery production, the impact of the BEV, followed by the hybrid car, is very high compared to the other technologies. The needed amount of lithium ion battery in the case of the BEV is heavier than the remaining part of the vehicle. However, more than 70% of the impacts induced by the lithium battery are balanced by its end-of-life treatment. In order to assess the influence of the type of electricity on the BEV results, the Belgian supply mix electricity has been replaced in the LCA model by renewable electricity modeled with 50% windpower and 50% hydropower. Thanks to the renewable electricity, the impact of the use phase of the BEV on human health has been lowered more than 5 times (Figure 6).

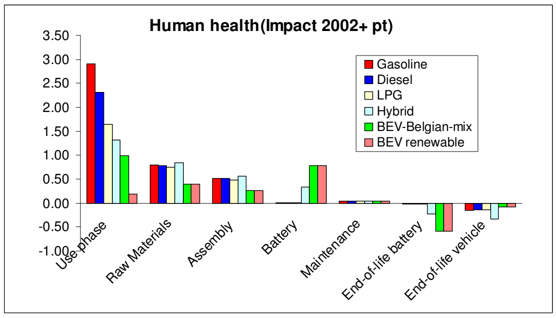

Figure 6: Human health step by step comparison of the different vehicle technologies

5 Sensitivity analysis

In a classic LCA, average values are used during the modeling of the life cycle of the product system. To perform a sensitivity analysis in such a model, the parameters should be changed manually for the introduction of each specific new value. As a range-based modeling system has been used in this study, all the possible values of each parameter are included in the model with respect to their distribution type. The results can be expressed both in terms of average values and in terms of ranges of values. Thanks to this approach, a permanent and automatic sensitivity analysis is performed at each impact calculations. In addition, the modeler is free to choose the number of iterations during the sensitivity analysis.

In Figure 7, the influence of the euro emission standard of a gasoline car on the respiratory effects has been assessed. The difference between the different cars is not clearly noticeable but euro 4 and 5 cars seem to have lower respiratory effects. As a preliminary conclusion, euro 4 and 5 seem to be better when dealing with respiratory effects.

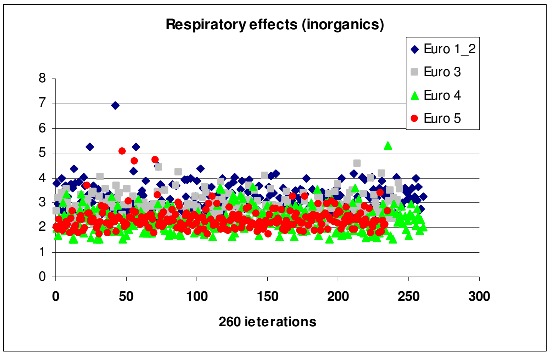

Figure 7: Influence of the euro emission standards on the respiratory effects

As the difference is not that clear for the respiratory effects, the same approach has been used for the same vehicle technology regarding the carbon monoxide emissions. Figure 8 clearly shows that euro 4 and 5 cars always emit less carbon monoxide than euro1, 2 and 3 cars within this vehicle segment.
Thanks to this sensitivity analysis, it has become possible to differentiate vehicles which have the same technology and the fuel, which belongs to the same segment and which have very close ranges of fuel consumption and CO_2 emissions but with different emission standards.

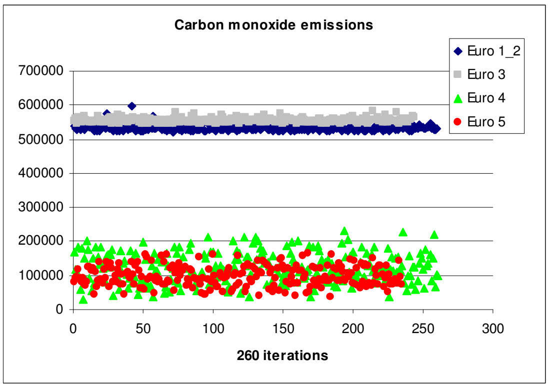

Figure 8: Influence of the euro emissions standards on carbon monoxide emissions

Conclusion

In this paper, it has been possible to calculate LCA results for electric hybrid, LPG, diesel and gasoline cars for vehicles registered as family cars in Belgium. Thanks to a range-based modeling system, the variations of the weight of the vehicles, the fuel consumption and the emissions are taken into account. It is important to notice that the ranking order of the different vehicle technologies depends on the considered impact categories. The greenhouse effect analysis shows that the Gasoline car has the worst score and the BEV the best one. The hybrid car is slightly better than the LPG car. These results are directly linked to the type and the consumption rate of fuels. The assessment of the air acidification and the impact on human health show the same trend. The best score goes to the BEV and the worst to the petrol car. The hybrid car is lightly better than the LPG one which is better than the diesel car. The results for theses two categories are directly linked to the emission of sulfur and nitrogen oxides.
The replacement of the Belgian supply mix electricity by a renewable one will lower more than 5 times the impact of use phase of the BEV on human health.

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