Life Cycle Assessment of conventional and alternative small passenger vehicles in Belgium

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***Abstract*-In this paper it is examined how environmentally friendly conventional and new vehicle technologies are and how their environmental effects can be compared. An automotive Life Cycle Assessment (LCA) is being performed for small family passenger vehicles in Belgium. Next to the well-to-wheel (WTW) emissions (related to fuel production, distribution and fuel use in the vehicle), the LCA also includes cradle-to-grave emissions (related directly and indirectly to the vehicle production, transportation, maintenance and the end-of-life (EoL) processing of the vehicle). The considered impact categories are: air acidification, eutrophication, human health and greenhouse effect (GHE). 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. The results show that the battery electric vehicle (BEV) has the best environmental score for all the considered impact categories. Petrol vehicles have the worst impact on the greenhouse effect, but hybridization of the drive train has a positive influence on this impact category. The impact of the hybrid vehicle is considerably lower than of the equivalent petrol vehicle. On the other hand, when assessing the acidification impact, one can notice that the hybrid car has a high impact. Without the recycling of the NiMH battery, the results for the hybrid vehicle would be even higher than for the equivalent petrol vehicle. This is due to the production of the nickel contained in the NiMH battery. Vehicles running on diesel have the highest impact on eutrophication. The tank-to-wheel (TTW) part contributes the most to the overall impact on eutrophication, as a result of the NO_X emissions. The evaluation of the impact on human health shows that the petrol vehicle has the highest impact, due to the high NO_X, particulate matter (PM) and SO_X (WTT) emissions.**

I. INTRODUCTION

The transportation sector is responsible for large quantities of pollutants in the atmosphere, which have local, regional or global effects on environmental receptors (people, materials, agriculture, ecosystems, climate, etc.) [1]. In Flanders, transport is accountable for 31% of the particulate matter (PM) emissions, 21% of the acidification (NH_3, NO_X, SO_2) and 17% of the greenhouse effect (CO_2, CH_4, N_2O, HFC, PFC, SF_6). Yearly a substantial growth of the transportation sector is observed in the EU, resulting in an increase of 1.2% for the period between 2006-2007. Taking into account the modal split, passenger cars round up for a total of 4688 billion passenger-kilometers (pkm) in 2007 for EU-27, with 72.4% market share this is the key mode for passenger transportation [2]

The focus of this paper is on passenger transportation and the influence of the different vehicle technologies on the environment.

There are different approaches to make the transportation sector more sustainable: (1) encouraging modal shifts (walking, cycling, public transport), (2) more efficient vehicles, with reduced energy consumption and low-carbon energy carriers, (3) changing driving behavior, and (4) controlling the need for motorized transportation [3]. Here the focus lies on the second approach (technical innovation), recognizing that pervasive solutions will involve a mixture of different options.

It is examined how environmentally friendly conventional and new vehicle technologies are and how their environmental effects can be compared. An automotive LCA at country level (Belgium) is specified in previous work [4] and is being extended in this paper. Important reports about the environmental performance of a vehicle are [5] [6] [7] and were used to benchmark the results.
The retained impact categories are: air acidification, eutrophication, human health and greenhouse effect (GHE). Since the Belgian fleet includes a large variety of cars, all the Life Cycle Assessment (LCA) modeling parameters are statistical distributions, resulting in a variation of the considered impacts. This provides a novel and useful method for exploring the environmental impacts of all vehicles on a market, reflecting the differences in terms of segment, technology, drive train, fuel, weight and emission standard.

II. METHODOLOGY

The comparison of the environmental impacts of different vehicles (petrol, diesel, LPG, hybrid and battery electric vehicles) is performed by means of a LCA, for a Belgian context. LCA is a standardized methodology [8]. Detailed description of the used methodology and assumptions can be found in [4]. Next to the well-to-wheel (WTW) emissions (related to fuel production, transportation and use in the vehicle), which is also assessed in the Ecoscore methodology [3], the LCA also includes cradle-to-grave emissions (related directly and indirectly to the vehicle production and end-of-life processing of the vehicle).

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The Functional Unit, which is the reference performance of the vehicle, has been defined as a lifetime driven distance of 230,500 km, corresponding to a vehicle lifespan of 13.7 years [9]. In this study detailed environmental impacts of the different vehicle technologies are assessed for the small family car segment. This car segment has a weight between 900 – 1600 kg and a length between 3.6 - 4.5 meters. The vehicle segmentation is based on the existing Ecoscore [3] and the FEBIAC [10] segmentation. It contains following segments: city car, supermini, small family car, family car, small monovolume, monovolume, exclusive car, sports car and SUV.

An extensive life cycle inventory step has been elaborated covering all the inputs and outputs from and to the environment from all the unit processes involved in the product system. The inventory is, in other words, an extensive list of all the needed materials, chemicals, energies and all the emissions related to the fulfillment of the functional unit. The life cycle inventory, which was created in the framework of the 'CLEVER' project, covers all the life cycle phases of conventional and alternative vehicles. It includes the extraction of raw materials, the manufacturing of components, the assembly, the use phase (on a well-to-wheel basis) and the end-of-life treatment. When specific Belgian data are not available, average European data are considered.
The tank-to-wheel (TTW) emissions from the Ecoscore database are used for the different market segments.

The Ecoinvent database [11] has been used to calculate Life Cycle Inventory (LCI) data for materials, manufacturing processes, energy production, fuel production and distribution involved in the life cycles of both conventional and alternative vehicles.
Detailed LCI data of different battery technologies for hybrid electric (HEV) and battery electric vehicles (BEV) have been collected from the SUBAT project [12]. Thanks to the OVAM study [13] on the vehicles' end-of-life in Belgium, all the recycling and energy recovery rates per material with respect to the real efficiency of Belgian recycling plants were collected.

The results of an LCA should be understood and interpreted in the context of the used impact calculation methods. The results presented in this paper, are produced with four calculation methods: the IPCC 2007 greenhouse effect over 100 years [14], the human health impact from [15], the air acidification impact calculation method from [16] and the eutrophication impact calculation method from [16].

For each specific impact calculation method, only the pollutants involved in the method are taken into account with respect to the characterization factor attributed to each pollutant. Diesel and petrol cars are divided in Euro 4 and Euro 5 emission standards to point out the possible relevance of the emission standard on the specific impact category.

III. Results and Discussion

Figure 1 illustrates the results of the calculated impacts on air acidification for the different considered vehicle technologies. The negative values are avoided impacts due to the recovery of materials in the end-of-life (EoL) recycling step. Figure 1 demonstrates that the battery electric vehicle using average Belgium electricity (BEV, BE mix) has the lowest impact on air acidification. The petrol vehicle has the largest impact on air acidification, this is due to the impact of the petrol production in which NO_x and SO_x are the leading emissions for the acidification impact. The influence of diesel production on acidification is lower compared to the petrol production. On the other hand are the TTW emissions of NO_x and SO_x of a diesel car higher. A positive trend can be distinguished for the TTW emissions, due to stricter European emission limits for NO_x en SO_x. The impact of the production of copper and steel are the main contributors for the 'raw material' phase. The acidifying emissions during the assembly of the car are introduced by the usage of electricity.
The calculation of the air acidification has also revealed that the production of a battery for a BEV (Lithium battery) and a hybrid vehicle (NiMH battery) has a large impact on the overall result. Without the recycling of the NiMH battery, the results for the hybrid vehicle would be even higher than for the equivalent petrol cars. This is due to the production of the nickel contained in the NiMH battery. The production of nickel is responsible for higher emissions of nitrogen oxides and sulphur oxides. Recycling is important when dealing with impacts on air acidification.

Figure 2 shows the results of the calculation of the impact on eutrophication. The main contributing emissions to the eutrophication impact are nitrogen oxides (NO_x), phosphorus and ammonia. Vehicles running on diesel have the highest impact. The TTW part contributes the most to the overall impact on eutrophication. This is due to the higher NO_x tailpipe emissions of diesel cars. For petrol vehicles, the WTT emissions are contributing more to the eutrophication impact than the TTW emissions. LPG and BEV are having the lowest impact on eutrophication. The Lithium battery production, needed for the BEV, has a large contribution to the eutrophication impact.

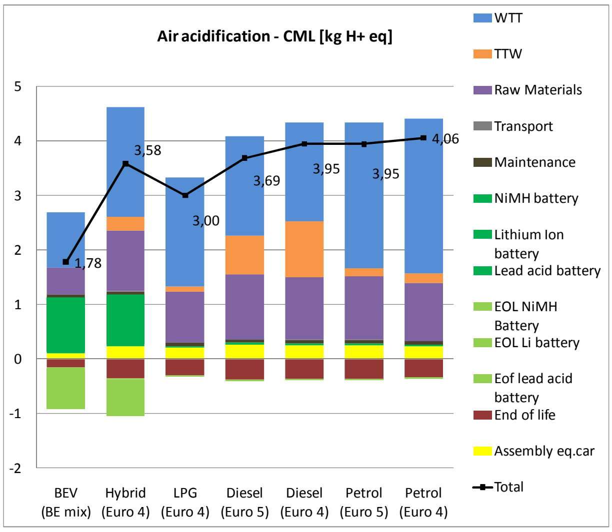

Fig 1. Contribution of the life cycle of a small family car to the impact on air acidification.

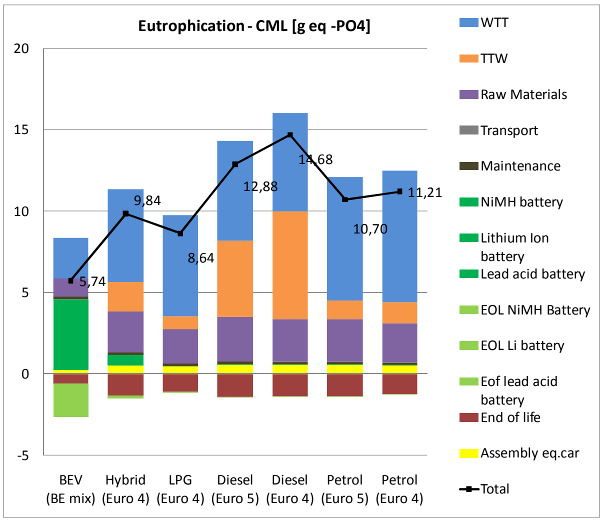

Fig 2. Contribution of the life cycle of a small family car to the impact on eutrophication

The BEV scores better than the other vehicles, when considering the human health impact category (Figure 3). In general it can be noticed, that the use phase (well-to-wheel) is responsible for the major part of the impact on human health, but the manufacturing step (extraction of raw materials, the production of the components and the assembly of the vehicle) contributes a great deal to the total impact as well. For the BEV this relevance of the manufacturing step is, due to the low contribution of the use phase, relatively more important. The BEV has no tailpipe emissions, however it produces tire and brake abrasion is caused during usage, which is included and has an important impact on human health.

The heavy metals contained in the fuels are included in the calculation of the human health impact category.

Thanks to stringent European emission limits for particulate matter, diesel vehicles (Euro 5) are having a better score than petrol vehicles when considering the impact on human health. This can be attributed to the higher impact of the petrol production, which is induced by the emission of SO_x, NO_x and PM.

However, the tailpipe emissions (NO_x and PM) of the diesel vehicle are still higher compared to the tailpipe emissions of the petrol vehicle. The impact of the vehicle production is induced by the production of steel and copper (SO_x, NO_x, PM and arsenic) and the needed electricity during the assembly phase (SO_x, NO_x, PM and dioxins).

Nowadays, the GHE is a very popular impact category, the results are shown in figure 4. Petrol vehicles have the largest impact on the Greenhouse Effect. The petrol vehicle has the highest fuel consumption, which explains the high WTT and TTW emissions. Thanks to the hybridization of the drive train, the hybrid vehicle manages to decrease fuel consumption and accordingly the impact on the greenhouse effect. As a consequence the hybrid vehicle has the lowest impact of all internal combustion engine vehicles, considered in this paper. The BEV has overall the lowest impact on the greenhouse effect.

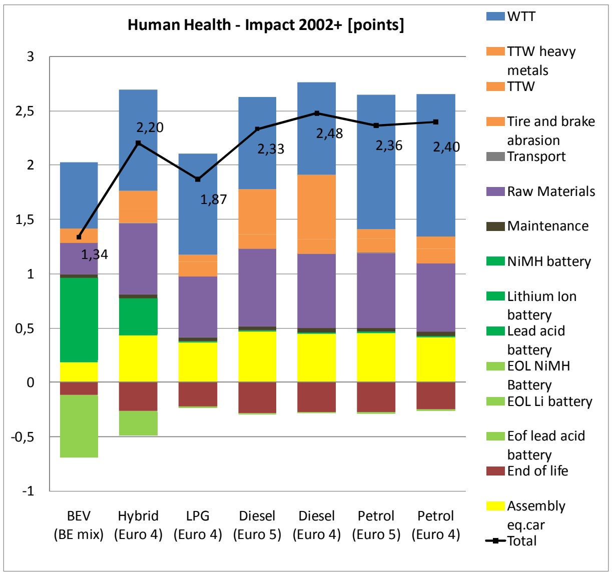

Fig 3. Contribution of the life cycle of a small family car to the impact on human health

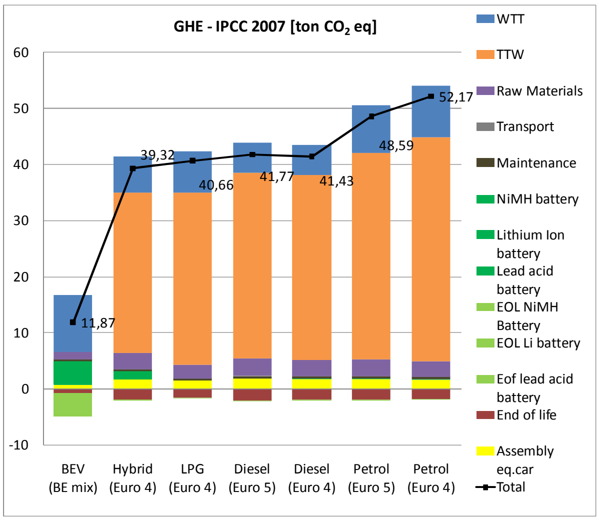

Fig 4. Contribution of the life cycle of a small family car to the impact on the greenhouse effect

Figure 5 shows the sensitivity of the environmental impact of a BEV to the type of electricity production. The included different feedstock for the electricity production plants are hydro, wind, nuclear, biogas, natural gas, oil and coal. The results are benchmarked against a BEV running on the Belgian electricity mix (approximately 46% nuclear, 21% natural gas and 9% coal) [17] and a Euro 5 petrol car. The first issue to notice is that the impact is highly depending on the type of electricity production and that the options with the highest impacts (oil, coal) are the most sensitive ones to variations in the electricity consumption. Coal and oil based electricity production plants are emitting much more air pollutants compared to other types of electricity production plants.

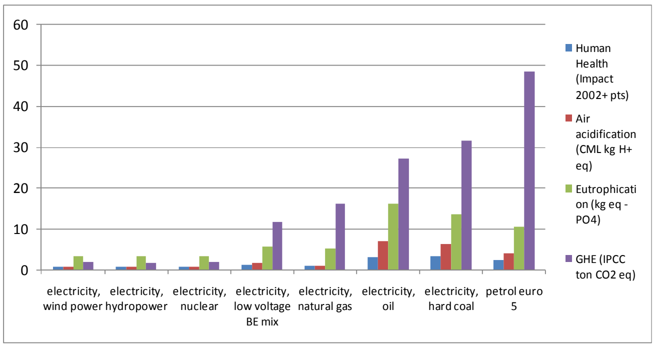

Fig 5. The influence of electricity production a BEV LCA study

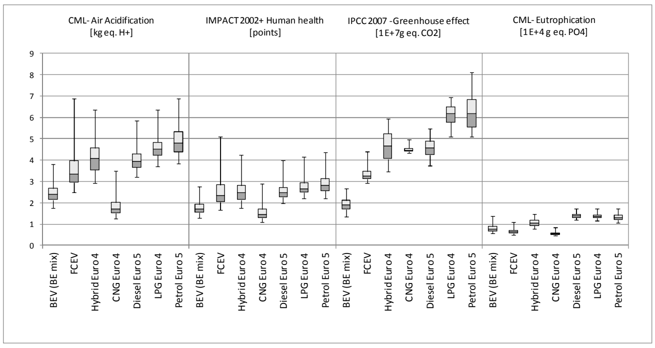

Fig 6. The sensitivity of the impacts to the variation of the LCA modeling parameters

In general, a BEV has a better score than a petrol vehicle except for the full coal or oil electricity production scenarios, for which the BEV can have a bad score for eutrophication, human health and air acidification. It must be mentioned that a full coal or oil electricity production are extreme scenarios, which will not occur in reality.

The Belgian electricity mix has a higher impact than the cleanest electricity production plants, but delivers a very good score compared to the petrol vehicle and a BEV running on this electricity is a first, feasible step towards cleaner passenger transportation. However, the production of electricity from renewable energy sources, such as hydro- and wind power, has a huge potential to lower transportation related emissions and impacts even further in the future.

The sensitivity of the impacts to the variation of the LCA modeling parameters is shown in figure 6 by means of a boxplot. The ranges for these parameters include all existing variations on the Belgian market. The different vehicle technologies available in the family car segment are investigated. In general the vehicles in the family car segment have larger values for weight and fuel consumption compared to small family cars, however the overall trend of the impacts is similar. This shows that segmentation does not have an influence on the differences between vehicle technologies.

The box-plots are a five-number summary of the distribution of the results, showing the interquartile range, the mean, the 98^{th} (maximum) and 2^{nd} (minimum) percentile.

Included vehicle technologies or fuels are BEV, fuel cell electric vehicle (FCEV), hybrid Euro 4 vehicle, compressed natural gas (CNG), diesel, LPG and petrol. CNG and BEV are having the smallest environmental impact for acidification, eutrophication and human health. For GHE it is clear that BEV has the best score. This is due to the high efficiency of the electric motor.

For the GHE, the BEV is most of the times better than a petrol equivalent car, but in some extreme scenarios a small fuel-efficient petrol car can have a better score regarding GHE than a large BEV running only on coal-produced electricity. However, when considering only the interquartile ranges, a switch from petrol to BEV is always advisable.

IV. CONCLUSIONS

In this paper, the LCA results are shown for four calculated impact categories (greenhouse effect, eutrophication, human health and acidification) for the different vehicle technologies being: battery electric, hybrid, LPG, diesel and gasoline vehicles registered in Belgium as small family cars.

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 in a sensitivity assessment.

For all the considered impact categories, the BEV has the best score. The calculations of the BEV are considering an average electricity production in a Belgium context. The influence of the electricity production on the overall result of a BEV is investigated.

The greenhouse effect analysis shows that the petrol vehicle has the highest impact. The hybrid car is slightly better than the LPG car, which is mainly explained by the hybridization of the drive train, which enables the hybrid car to decrease its fuel consumption. On the other hand, when assessing the air acidification, one can notice that the hybrid car has a high impact. Without the recycling of the NiMH battery, the results for the hybrid vehicle would be even higher than for the equivalent petrol car. This is due to the production of the nickel contained in the NiMH battery. Vehicles running on diesel have the highest impact on eutrophication. The evaluation of the impact on human health shows that the petrol vehicle has the worst score, due to the high NO_x and SO_x tailpipe emissions. Thanks to strict European emission limits for particulate matter, diesel vehicles are even having a better score than petrol vehicles when considering the impact on human health. It is important to mention that the Lithium battery seems to be less dangerous for the human health compared to the NiMH battery.

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