Energies **2014**, *7*, 1467-1482; doi:10.3390/en7031467

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels

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*Received: 4 December 2013; in revised form: 25 February 2014 / Accepted: 3 March 2014 /
Published: 11 March 2014*

Abstract: How to compare the environmental performance of different vehicle technologies? Vehicles with lower tailpipe emissions are perceived as cleaner. However, does it make sense to look only to tailpipe emissions? Limiting the comparison only to these emissions denies the fact that there are emissions involved during the production of a fuel and this approach gives too much advantage to zero-tailpipe vehicles like battery electric vehicles (BEV) and fuel cell electric vehicle (FCEV). Would it be enough to combine fuel production and tailpipe emissions? Especially when comparing the environmental performance of alternative vehicle technologies, the emissions during production of the specific components and their appropriate end-of-life treatment processes should also be taken into account. Therefore, the complete life cycle of the vehicle should be included in order to avoid problem shifting from one life stage to another. In this article, a full life cycle assessment (LCA) of petrol, diesel, fuel cell electric (FCEV), compressed natural gas (CNG), liquefied petroleum gas (LPG), hybrid electric, battery electric (BEV), bio-diesel and bio-ethanol vehicles has been performed. The aim of the manuscript is to investigate the impact of the different vehicle technologies on the environment and to develop a range-based modeling system that enables a more robust interpretation of the LCA results for a group of vehicles. Results are shown for climate change, respiratory effects, acidification and mineral extraction damage of the different vehicle technologies. A broad range of results is obtained due to the variability within the car market. It is concluded that it is essential to take into account the influence of all the vehicle parameters on the LCA results.

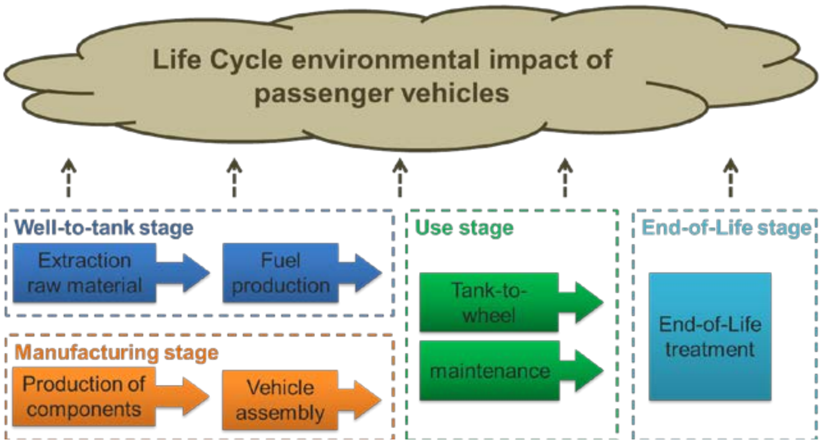
Keywords: life cycle assessment; electric vehicles; green cars; sustainable mobility; environmental impact; uncertainty

1. Introduction

The transportation sector is responsible for the emission of large quantities of pollutants to the atmosphere, which have local, regional or global effects on environmental receptors (people, materials, agriculture, ecosystems, climate, *etc.*) [1]. In the European Union, the transport sector is accountable for 18% of the particulate matter (PM) emissions, 39% of the acidifying NO_x, 36% of the CO, 25% of the CO_2 emissions and 31% of the energy usage [2,3].

The aim of this article is to investigate the impact of the different vehicle technologies on the environment and to provide a robust interpretation, including statistical distributions. The focus of the paper is on passenger cars. In the literature, well-to-wheel (WTW) assessments are often used to compare various vehicle technologies [4]. A WTW assessment only considers the production of the fuel or electricity (Well-to-Tank) and the tailpipe emissions (Tank-to-Wheel). This creates a bias towards zero-tailpipe emission vehicles, as the environmental impacts associated with the production of specific components, such as batteries, are not taken into consideration in a WTW study. A life cycle assessment considers the full life of a product system and is not only limited to the production and usage of the fuel or electricity. It includes the extraction of raw materials, the manufacturing of components, the assembly, the use stage (on a well-to-wheel (WTW) basis) and the end-of-life (EoL) treatment, see Figure 1. Thanks to the LCA methodology the environmental impacts are not limited to a potentially misleading WTW basis.

Figure 1. Schematic representation of the different life cycle stages of a vehicle.



The environmental impacts of different fuels and vehicle technologies are evaluated with the Life Cycle Assessment (LCA) methodology. LCA is a standardized methodology [5,6]. A detailed description of the methodology, assumptions, inventory and model can be found in [7].

Many LCA studies dealing with vehicles or components exist [8–18]. Often, vehicle-LCA studies provide contradictory results, depending on the data and modeling assumptions used, making it difficult for policy makers to formulate solid decisions. Often the environmental impact of a vehicle calculated with life cycle assessment is shown as a single value. This approach approximates the environmental impact of one vehicle, but fails to provide decision-makers with a wide view of the possible effects of their decisions. The complexity, uncertainty and variability of the system are not well approximated with a single value. For instance, when choosing a single car and comparing it with another single car, the full quality of the comparison falls or stands with the chosen set of vehicles. The variation of one single parameter such as fuel consumption or the weight of a car within one given vehicle technology and segment can lead to different results and interpretations. It is therefore essential to take into account the influence of all the vehicle parameters on the LCA results. This paper is an update and a thorough extension of the work first presented at the 2012 Urban Transport Conference [19].

The main objective of the manuscript is to develop a range-based modeling system that enables a more robust interpretation of the LCA results of a group of vehicles. The variability of the key environmental performance indicators of the vehicles on the market is included in the LCA model. Uncertainty is an inherent part of LCA and should be considered in the end result.

2. Goal and Scope

The manuscript aims to analyze the life cycle impact of all the family cars registered in Europe in 2011 on the one hand, and to assess the influence of vehicle parameters on the LCA results on the other hand. The objective of the paper is to create an objective image of the environmental impact of vehicles with conventional and alternative fuels and/or drive trains. The raw material production, transport, manufacturing, use, maintenance and end-of-life of all the vehicles are all taken into account. The vehicle specific data such as the fuel type, fuel consumption, Euro standard, weight and direct emissions are retrieved from an extensive vehicle database based on data mainly gathered by the Belgian federal service in charge of vehicle registration [20]. An attributional LCA modeling framework has been used.

The functional unit (FU) is a quantified description of the performance of product systems, for use as a reference unit. It allows comparing two or several product systems on the basis of a common provided service. In this paper, the functional unit is defined as driving 1 km in Europe. The functional unit takes all life cycle stages of the vehicle into account and assumes an average lifespan of 13.7 years and a total life mileage of 230,500 km [21]. The total life time refers to the age of the average vehicle going to the end-of-life treatment in Belgium.

3. Life Cycle Inventory

A short description of the main parts of the Life Cycle Inventory is summarized in this section. Detailed tables can be found in the additional information that is provided with this manuscript.

3.1. Manufacturing

The LCI data of the Volkswagen Golf A4 vehicle [22] has been adapted to model the manufacturing stage of all the internal combustion engine (ICE) vehicles with respect to their specific weights. This only applies for the scalable parts, which mainly refers to the body shell of the vehicles. The environmental impact analysis revealed that these parts have a small contribution to the overall impact. All other components are modeled specifically and in detail per technology group, as these components (for example battery, electric motor, fuel cell, *etc*.) have a significant contribution to various impact categories. Individual data was gathered for the specific components of the different vehicle technologies, such as BEV and FCEV. In this manuscript, a typical sedan-specific catalytic converter is considered. The LCI includes all the materials of the converter and all the manufacturing processes [23].

LCI data of batteries were collected from the SUBAT project [24,25]. The LCI covers both hybrid electric vehicles (HEV) and battery electric vehicles (BEV). The hybrid vehicle is equipped with a NiMH battery and the battery electric vehicle uses a lithium-manganese battery. The lithium-manganese battery was modeled as this is the chemistry used in the Nissan Leaf. The ratio between the life time driven distance (230,500 km) and the cycle life of the lithium-ion battery (100,000 miles or 160,934 km) [26] has been used to calculate the number of batteries needed for the BEV. However, this might overestimate the number of needed lithium-ion batteries as the loading of the battery in a Tesla is different compared to a Nissan Leaf. Furthermore, the battery cycle life will vary in reality as it is a function of how the battery is charged, discharged and climatic circumstances.

Because of the use of special materials during the production of the fuel cell and the hydrogen tank of fuel cell electric vehicle (FCEV), the manufacturing data of this vehicle technology have been gathered and treated separately. Material breakdown and energy consumption for the production of the fuel cell and the hydrogen tank have been gathered from [27]. The technical specifications of the Honda FCX Clarity [28] have been used to adapt the weight of the fuel cell, the tank, the electric motor and the controller.

3.2. Well-to-Tank

The use stage of the vehicles is split up into Well-to-Tank (WTT) and Tank-to-Wheel (TTW). The WTT part covers the production and the distribution of the fuel while the TTW phase covers the use of this fuel by the vehicle.

To evaluate the environmental performance of electric vehicles in Europe, the European electricity supply mix has been used. For a fair comparison with other vehicle technologies an electricity supply mix should be chosen over a specific electricity technology as coal or natural gas plants. The life cycle inventory of the electricity supply mix includes the shares of electricity production per type of technology. However, the sensitivity of the environmental impact of a BEV to the type of electricity generated is investigated in more detail in the manuscript, as the type of electricity is seen as a key influencer in literature [29].

In this manuscript, hydrogen production via steam reforming (SMR) of natural gas is considered [30] since worldwide it accounts for more than 90% of current hydrogen production. The production of the natural gas, the electricity production, the construction and the decommissioning of the reforming plant and the construction of the natural gas pipeline are taken into account in the LCI.

For diesel and petrol production, all the processes in the refinery are taken into account. It includes the waste water treatment, process emissions and direct discharges into rivers. Major indicators like energy use have been estimated based on a survey in European refineries [31].

Two groups of first generation bio-fuels are discussed in this manuscript: oil-based biofuels and ethanol. Ethanol from sugar cane produced in Brazil has been considered. For the generation of biodiesel, rapeseed methyl ester (RME) is considered.

3.3. Tank-to-Wheel

The Tank-to-Wheel (TTW) part considers the tailpipe emissions and the fuel (or energy) consumption. The average CO_2 emissions (g/km) as well as the HC, SO_2, NO_x, CO, PM, CH_4, N_2O emissions (g/km) for each specific vehicle are taken into account. The fuel consumption and the emissions are measured according to the New European Driving Cycle (NEDC) for all vehicles on the European market and can be found in [32]. In the specific case of biofuels vehicles, the TTW emissions and fuel consumption have been gathered from the BIOSES project [33].

3.4. Maintenance

A maintenance stage has been modeled, containing lubricant oil consumption, tires and washing water during the lifespan of the vehicle. The theoretical maintenance process corresponds to a Golf A4 diesel and is used to fulfill the functional unit. The calculations are based on the assumptions of the IMPRO-car project [34] and the Life Cycle Inventory for the Golf A4 [22].

3.5. End-of-Life

An energy consumption of 66 kWh/t [35] is considered for the shredding and the further separation processes for the body shell. As batteries in end-of-life vehicles should be removed and treated separately during the depollution step of end-life vehicles, their treatment has been assessed separately.

Including an appropriate end-of-life treatment is essential to provide a full life cycle overview of the environmental impact of new components. In [14] the impacts associated with the material recovery and disposal processes are allocated to the vehicle, however, the benefits of recovering materials that can be used in future products are not taken into consideration. In underlying paper, recovered materials are credited to the vehicle as it avoids future material production from virgin ores.

Different recycling processes have been considered according to the battery technology: Hydrometallurgical process for lithium ion technology, pyro metallurgical for NiMH technology and the Campine process for Lead acid technology [36].

4. Range Based LCA

After the completion of the Life Cycle Inventory, the different elementary flows that are linked to the product system need to be converted into environmental indicators. These indicators allow quantifying and comparing the potential environmental impacts of the different vehicle technologies.

This step of the LCA is called Life Cycle Impact Assessment (LCIA). As required by [6]. The selected impact categories and their appropriate methods are: climate change [37], air acidification [38], mineral extraction [39] and respiratory effects (inorganics) [40].

For each specific vehicle group (defined by segment, technology and euro standard), the fuel consumption, the weight and the different emissions are the variables that can have an impact on the final result. That is why for these variables the possible ranges are being used as input for a Monte Carlo simulation.

The existence of different cars with different parameters leads to a spread of LCA results. This is shown in the results with error bars. The ranges of weight and fuel consumption can be found in Table 1 for the different vehicle technologies. No weight variation has been considered for specific cases (FCEV, BEV, E 85, CNG and B100) where only one vehicle is available. However, a variation in the fuel consumption is considered, as this influence the result significantly. The ranges of the tailpipe emissions (CO_2, CO, NO_x and HC can be found in Table 2). Tables 1 and 2 show the minimum, arithmetic mean and maximum values for the different parameters. The values are based on a data analysis of the "ecoscore" database containing over 200,000 different, real vehicles [32]. This database contains all the vehicles that are on the Belgian road. The probability distribution of the parameters is described as a statistical distribution using the Chi-Square goodness-of-fit test. This statistical test is used to fit a uniform, triangular, normal or lognormal distribution to the data. The 95% significance interval has been used. To investigate the correctness of the sample size the standard error of mean is calculated (standard deviation of sample means). With a sample size of 1000 a small standard error was obtained with the Monte Carlo assessment.

Table 1. Ranges of weight and fuel consumption of different family cars.

Name	Weight (kg)	Fuel consumption	Unit
Petrol (Euro 4)	(883, 1227, 2438)	(5.6, 7.1, 13.7)	l/100 km
Petrol (Euro 5)	(1304, 1474, 1923)	(7.1, 7.2, 11.9)	l/100 km
LPG (Euro 4)	(1282,1527,1684)	(9.5, 13.1, 13.6)	l/100 km
Diesel (Euro 4)	(1011, 1351, 2293)	(4.3, 5.3, 9.3)	l/100 km
Diesel (Euro 5)	(1200, 1519, 1883)	(4.5, 5.9, 7.2)	l/100 km
E85 (S. cane)	1299	(12.1, 12.2, 12.3)	l/100 km
E85 (S. beets)	1299	(12.1, 12.2, 12.3)	l/100 km
B100 (RME)	1255	(6.0, 6.1, 6.2)	l/100 km
Hybrid (Euro 4)	(1260, 1623, 1937)	(4.3, 6.1, 7.9)	l/100 km
CNG (Euro 4)	1470	9	Nm^3/100 km
FCEV	1625	(0.008, 0.01, 0.012)	kg/km
BEV	1223	(0.1, 0.17, 0.24)	kWh/km

Table 2. Ranges of CO_2, HC, NO_x and CO tailpipe emissions of different family cars.

Name	CO_2 (g/km)	HC (g/km)	NO_x (g/km)	CO (g/km)
Petrol (Euro 4)	(129, 170, 334)	(0.011, 0.058, 0.098)	(0.002, 0.018, 0.077)	(0.029, 0.295, 0.966)
Petrol (Euro 5)	(161, 167, 290)	(0.021, 0.036, 0.066)	(0.011, 0.019, 0.050)	(0.048, 0.247, 0.622)
LPG (Euro 4)	(155, 218, 227)	(0.038, 0.063, 0.066)	(0.041, 0.068, 0.073)	(1.000, 1.000, 1.000)
Diesel (Euro 4)	(110, 139, 255)	(0.070, 0.070, 0.070)	(0.124, 0.234, 0.249)	(0.003, 0.107, 0.362)

Table 2. *Cont.*

Name	CO_2 (g/km)	HC (g/km)	NO_x (g/km)	CO (g/km)
Diesel (Euro 5)	(116, 155,192)	(0.060, 0.060, 0.060)	(0.105, 0.169, 0.171)	(0.032, 0.187, 0.403)
E85 (S. cane)	(191, 192, 194)	(0.0009, 0.001, 0.0013)	(0.018, 0.025, 0.044)	(0.128, 0.163, 0.169)
E85 (S. beets)	(191, 192, 194)	(0.0009, 0.001, 0.0013)	(0.018, 0.025, 0.044)	(0.128, 0.163, 0.169)
B100 (RME)	149	(0.013, 0.017, 0.019)	(0.707, 0.710, 0.719)	(0.012, 0.012, 0.013)
Hybrid (Euro 4)	(102, 145, 187)	(0.010, 0.026, 0.055)	(0.001, 0.026, 0.050)	(0.100, 0.111, 0.309)
CNG (Euro 4)	161	(0.048, 0048, 0.048)	(0.056, 0.056, 0.056)	(0.358, 0.358,0.358)
FCEV	0	0	0	0
BEV	0	0	0	0

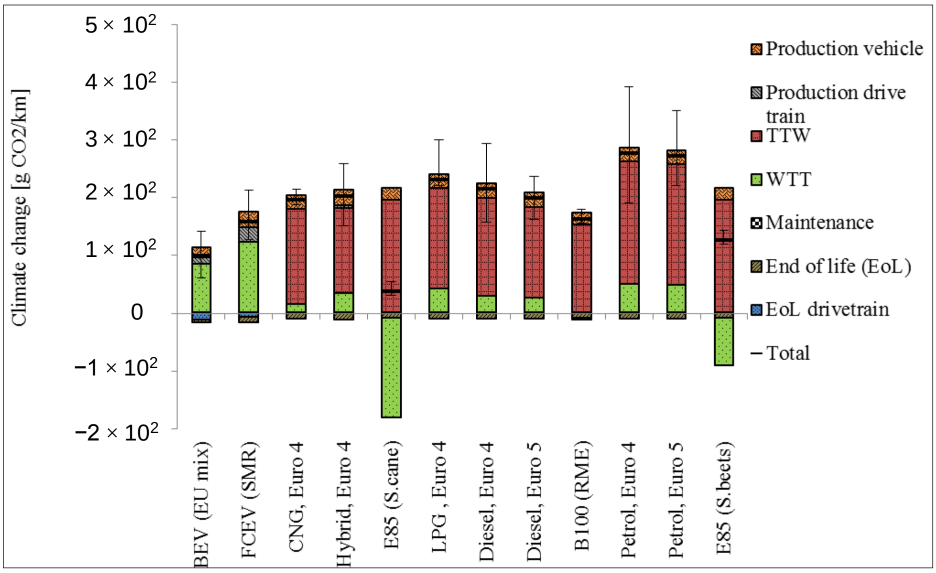
5. Results and Discussion

Different vehicle technologies are compared on their environmental merit; following environmental impact categories are discussed: climate change, respiratory effects, acidification and mineral resource depletion. The results contain all the life stages of a vehicle: Well-to-Tank (the production and distribution of the fuel and electricity), Tank-To-Wheel (including tailpipe emissions as well as road, tire and break abrasion), vehicle production (including the production of raw materials, components and the assembly), production drivetrain (including lithium batteries, the NiMH batteries, fuel cells, hydrogen tanks, electric motors and controllers) and the End-of-Life of the vehicle and the drive train (including recycling, incineration and landfilling).

5.1. Climate Change

The comparison of different family car technologies shows that the climate impact is highly influenced by the vehicle technology, the type of fuel and the type of feedstock used to produce the fuel (Figure 2). One can notice in Figure 2 that the sugar cane-based E85 (85% ethanol) vehicle has the lowest greenhouse effect. This is due essentially to the benefit of the CO_2 uptake from the air during the production of the sugar cane. Additionally, the electricity used in the sugar cane fermentation plant is produced with the bagasse obtained after the crushing of the sugar cane. However, this good score of the E85 highly depends on the feedstock type and, e.g., shifting from sugar cane to sugar beets will increase the impact of the E85 vehicle more than three-fold. After the sugar cane-based E85 vehicle, the BEV (battery electric vehicle) using the European supply mix electricity has the lowest greenhouse effect. The contribution of the lithium ion battery to the overall impact is significant. However, a big share of the impact of the lithium battery is balanced by the benefit the recycling. In general, for alternative vehicles such as FCEV and BEV the recycling of specific components such as the fuel cell or the lithium battery has a big environmental benefit, as the recycled materials are modeled as an avoided virgin material production. Like the BEV, the FCEV is also an exhaust emission free vehicle but it has a greenhouse effect higher than the BEV and comparable to the B100 (RME) one. The difference between the FCEV and the BEV is essentially due to the fact that the hydrogen is produced with natural gas. CNG vehicles have a lower impact on climate change in comparison to alternative vehicles such as hybrid and LPG.

Figure 2. The effect of various vehicle technologies on climate change.

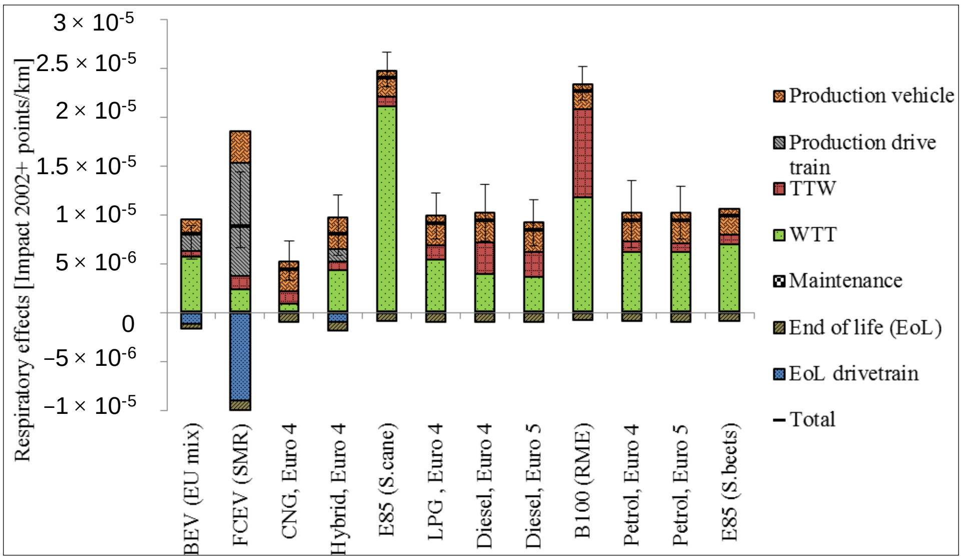


In order to have a deeper understanding of the results of this study, the LCA model takes into account the variability of the individual vehicles. In Figure 2 the effect of taking the variability into account is visualized with error bars showing the minimum, mean and maximum value of the statistical distribution of the result after Monte Carlo simulation. Extreme values corresponding to 2% of the iterations have been excluded. Extreme values are determined with the interquartile range in mind. Thanks to the Monte Carlo Assessment, the effect of the simultaneous variation of the vehicle weight, the energy consumption and the emissions has been assessed. With such an approach, stronger conclusions are drawn.

5.2. Respiratory Effects

Many studies are assessing the climate change effect of vehicles and are especially set up to find ways to reduce CO_2 emissions [29,41]. However, there are other important environmental impacts to consider. The respiratory effects of the different family car technologies have been compared in Figure 3. Contrarily to the GHE, the E85 sugar cane technology has the highest impact on respiratory effects. This is mainly due to the burning of the sugar cane field before the harvest. The main pollutants emitted during the field burning are carbon monoxide, methane and particles [42]. It is followed by the B100 (RME) vehicle. The high respiratory effect of the B100 (RME) vehicle is mainly due to the emission of ammonia and nitrogen oxides which are directly linked to the use of nitrogen based mineral fertilizers. The best score in this impact category goes to the CNG vehicle. The production of the natural gas has relatively low emission for all the considered pollutants in this category. This is also true for the direct emissions of the CNG vehicle. The CNG technology is followed by the BEV.

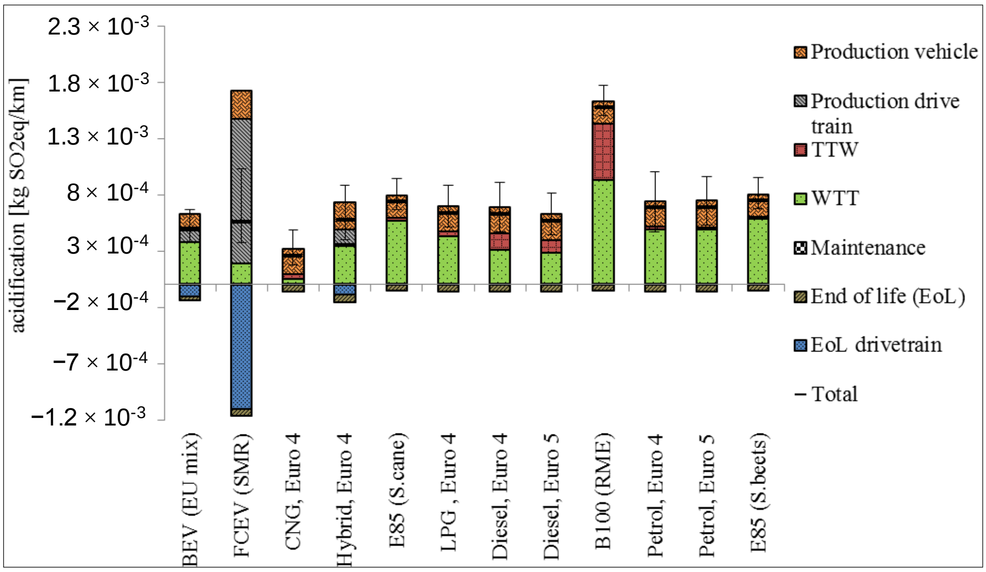
Figure 3. Respiratory effects of different family car technologies.



5.3. Acidification

The RME vehicle has the worst score on acidification and pollutes two times more than diesel vehicles (Figure 4). The main contributing pollutants are nitrogen based emissions, sulfur based emissions and fluoride and chloride acids. The production of platinum contained in the fuel cell has a large acidification impact but this impact is balanced by the recycling of the fuel cell. The benefit of switching from petrol to hybrid can also be seen in Figure 4. The hybrid vehicle has lower petrol consumption in comparison to the conventional petrol vehicle. However the higher contribution of the NiMH battery to acidification can be seen on the figure. Finally, it can be noticed that the acidification impact of diesel vehicles are lower than the impact of petrol. This is due to the fact that the production of petrol emits more NO_x than the production of diesel. However, diesel vehicles emit more NO_x during the TTW stage.

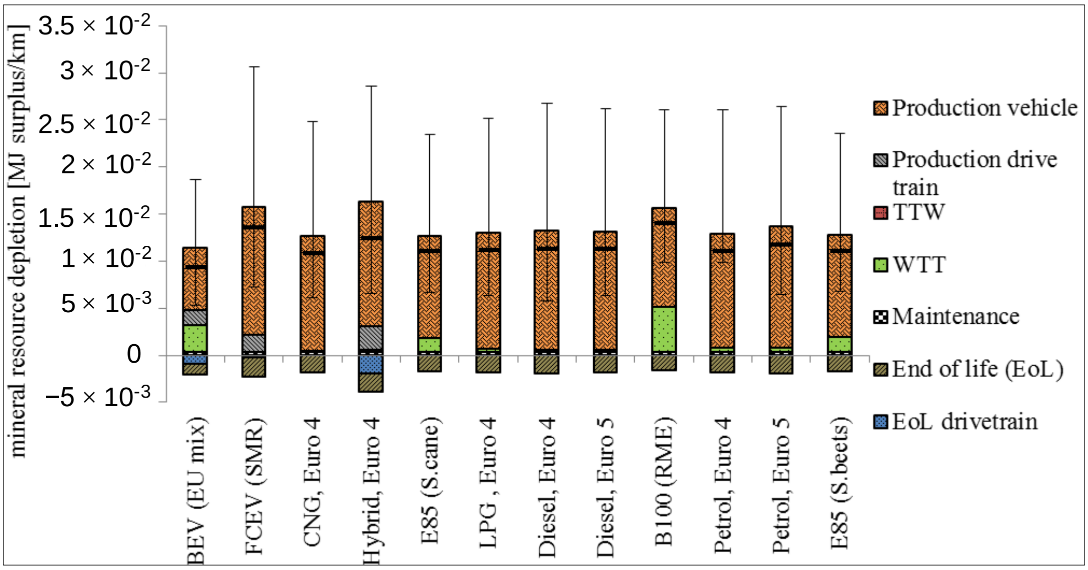
Figure 4. Acidification impact of different family car technologies.



5.4. Mineral Resource Depletion

The use of mineral resources is a key issue in the manufacturing, the use and the maintenance of vehicles and is shown in Figure 5. For this impact category, the size of a vehicle and the use of specific components requiring specific materials are the influencing parameters. Hybrid vehicles and FCEV have a higher impact for this indicator because of the use of specific and rare materials to produce components like the NiMH battery, fuel cell and hydrogen tank. The BEV has slightly lower mineral resource damage but the contribution of the lithium battery is still high. Another finding for this indicator is the high contribution of the transport and distribution of the electricity used to power the BEV. This is essentially due to the use of copper in the electric cables. It is important to mention that an increase of the size of a BEV will quickly increase its mineral extraction damage. The RME vehicle has a higher impact than petrol and diesel and is comparable to hybrid and FCEV. This is due to the use of mineral fertilizers during the rapeseed production. Figure 5 reveals the importance of recycling vehicular components such as batteries and fuel cells (FCEV, hybrid, BEV, *etc.*).

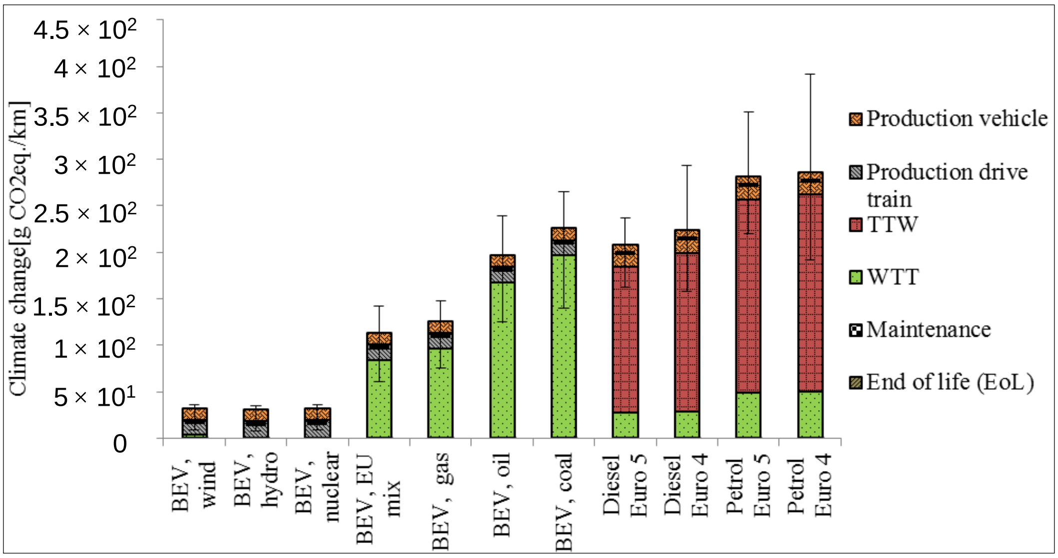
Figure 5. Mineral extraction damage of different family car technologies.



5.5. Influence of Electricity Production

In Figure 6, the influence of the electricity production technology on the LCA results of BEVs is discussed. The type of electricity production is the main driver for the LCA result of a BEV. The BEV powered with wind power, hydropower or nuclear power has very low greenhouse effect. They are followed by the results for the European electricity mix and the natural gas electricity, which all have lower greenhouse effects in comparison to diesel and petrol vehicles. However, in an extreme scenario in which BEVs are powered with oil or coal electricity, BEVs have climate impacts which are comparable to those of diesel cars. On average, the impact on climate change of petrol cars is still higher than the one of BEV powered with oil or coal electricity. Nevertheless, the error bars in Figure 6 show that small petrol cars within the family car segment can have a greenhouse effect which is comparable to a BEV powered by coal or oil electricity.

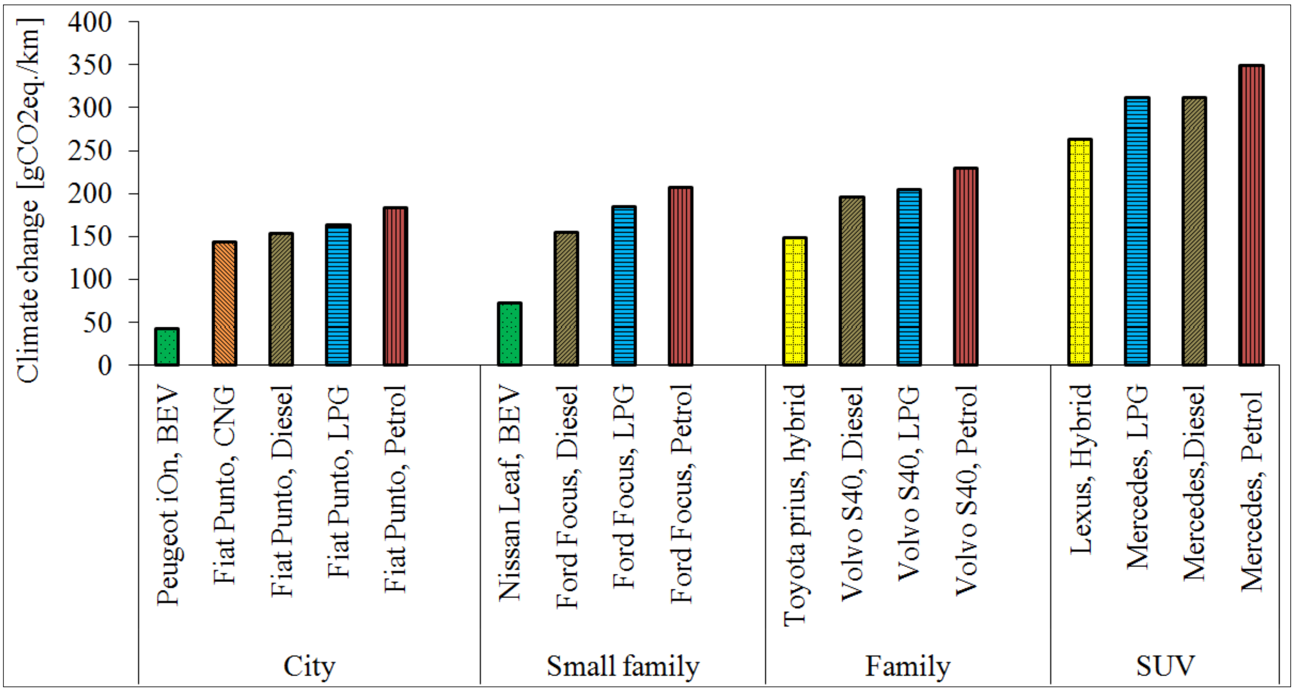
Figure 6. Sensitivity of the climate change impact of battery electric vehicles (BEV) to the type of electricity production.



5.6. Comparison of Reference Vehicles

The results which are discussed in the above paragraphs reflect the overall situations of different vehicle technologies. The error bars in the different results consider the variation of the vehicles in terms of different weights, fuel consumptions and emissions. This approach shows the LCA result of a whole group of vehicles.

Figure 7. Climate change impact of different car segments and technologies.



A list of reference vehicles, which are considered to be representative of their respective segment, has been made. The aim is to perform a fair comparison between equivalent vehicles because sometimes a limited number of vehicles with high weight or high fuel consumption can influence the average result of a full segment for a given technology. The individual comparison of the reference vehicle for GHE (Figure 7) gives the same ranking trend as in the Figure 2 for the different vehicle technologies. However, Figure 7 shows that the differences between the different technologies, especially the difference between petrol and diesel, are smaller than in the overall comparison. Moreover, Figure 7 shows that the segment also has a big influence on the LCA results. For example, a petrol family car will have a lower GHE than a hybrid SUV.

6. Conclusions

Comparing the environmental impact of conventional and alternative vehicles is a challenging exercise. This manuscript uses a novel approach in which the variability of important vehicle parameters is used to come up with a robust environmental comparison of vehicles.

To fairly compare all vehicular fuels and technologies (petrol, diesel, LPG, CNG, HEV, BEV, FCEV, biofuels, hydrogen), not only the well-to-wheel emissions but also the emissions due to the production, maintenance and end-of-life stage of the vehicle should be considered. In electric vehicles for instance, large batteries or a fuel cell, which are not present in conventional vehicles, have a significant environmental impact. However, to have a full overview of the impact of new components, the appropriate end-of-life treatment should be considered. The underlying assumptions in the LCA should always be clearly mentioned. Many times differences in LCA publications of vehicles can be explained by the differences in assumptions.

In order to be able to consider all life cycle stages, components and emissions in a life cycle assessment of the full car market, a range-based LCA model is developed. This model contains various car segments (city car, family car, SUV, *etc.*) and incorporates the market variability. The LCA model does not calculate the impact of selected vehicle, as the selection of a single vehicle can create a bias towards a specific technology. All vehicle technologies have the same comparison basis: driving 230,500 km for 13.7 years.

Many studies in literature focus solely on climate change. This focus neglects the fact that burden shifts are possible from one impact category to another. In this paper the list of selected environmental impact categories is extended and includes: climate change, respiratory effects, acidification and mineral resource depletion.

The environmental impact of a vehicle calculated with life cycle assessment is often shown as one single value. This approach approximates the environmental impact of one vehicle, but fails to provide decision-makers with a wide view on the possible effects of their decisions. The complexity, uncertainty and variability of the system are not well approximated with one single value. For instance, when choosing one single car and compare it with one other car, the full quality of the comparison falls or stands with the chosen set of vehicles. The variation of one single parameter such as fuel consumption or the weight of a car within one given vehicle technology and segment can lead to different results and interpretations. It is therefore essential to take into account the influence of the vehicle parameters on the LCA results.

Conventional vehicles using fossil fuels have the largest impact on climate change. On average diesel vehicles have lower impacts on climate change compared to petrol vehicles as they tend to consume less fuel, but the statistical assessment shows a large overlap between petrol and diesel vehicles. Hybridization has a positive effect on climate change. Battery electric vehicles have the lowest impact on climate change, with the exception of the bioethanol vehicle using fuel produced from sugar cane. The energy source used to generate the electricity is of crucial importance. When producing electricity solely from oil or coal the impact on climate change can be as high as in the case of conventional vehicles. The benefit for biofuels on climate change is due to the carbon uptake during the growth of the crop. The type of crop that is used to produce the biofuel influences the effect on climate change largely as the N_2O emissions from the usage of fertilizers has a significant impact.

When investigating the respiratory effects and the impact on acidification it is observed that biofuels have a large impact. Petrol and diesel vehicles have a lower respiratory effect compared to biofuel-using vehicles.

When analyzing the impact on mineral resource depletion, the production of the vehicle and its components stands out as the main important life cycle stage to consider. All vehicle technologies that are using specific rare earth materials in their drive train have a more significant impact. Fuel cell electric, hybrid and battery electric vehicles have the highest impact due to the use of specific materials in the fuel cell, the NiMH battery and the lithium battery. However, recycling these components reduces the impact significantly. The selection of the vehicle segment has an influence on the environmental impact. Segments dominated by larger, heavier vehicles have a larger impact.

Acknowledgments

This research has been made possible thanks to the support and funding of the Belgian Science Policy through the Science for a Sustainable Development (SSD) program. In this Framework the CLEVER “Clean Vehicle Research: LCA and policy measure” project was carried out by Vrije Universiteit Brussel, Université Libre de Bruxelles; Vlaamse Instelling voor Technologisch Onderzoek (VITO) and RDC Environment.

Author Contributions

Maarten Messagie focused on the uncertainty propagation in the research and statistical distribution of the results. Faycal-Siddikou Boureima focused on the Life Cycle Inventory. Thierry Coosemans, Cathy Macharis and Joeri Van Mierlo supervised the research and contributed in writing the result, discussion and conclusion section.

Conflicts of Interest

The authors declare no conflict of interest.

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