Environmental breakeven point: an introduction into environmental optimization for passenger car replacement schemes

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Abstract

This paper gives insights in how to introduce environmental aspects in automobile replacement policies. These policies aim at accelerating the adoption of cleaner vehicles by taking old vehicles out of the fleet, while supporting the vehicle industry. A scrappage policy must take the whole life cycle of a vehicle into account. Scrapping an old vehicle and manufacturing a new one creates additional environmental impacts which must be taken into consideration. This analysis is based on the comparison of the well-to-wheel (WTW) emissions with the cradle-to-grave (manufacturing, dismantling, recycling and waste treatment) emissions for vehicles with different ages, Euro standards and technologies. Optimizing vehicle's LTDD (Life Time Driven Distance) causes an LCA (Life Cycle Assessment) challenge, combining two contradictory environmental engineering concepts. Letting a vehicle have a longer use phase avoids specific impacts during manufacturing, such as mineral extraction damage and energy usage. Conversely, replacement of an old vehicle with a new, more efficient one can lower the impacts introduced during the use phase. To differentiate between vehicle technologies it is investigated how long it takes until a newly produced car has an environmental return on investment. This period is called the environmental breakeven point.
Keywords: environmental breakeven point, life cycle assessment, scrappage schemes, sustainable mobility, well-to-wheel analysis, electricity production.

WIT Transactions on The Built Environment, Vol 128,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/UT120041

1 Introduction

The energy consumption and the exhaust emissions of new vehicles have decreased considerably the last years, driven by European emission standards, technological exhaust treatment improvements and efficient engine technologies. These technological transitions towards a more sustainable transportation system are encouraged by two main drivers: the availability of energy sources (political and economic dependence on oil producing countries and the depletion of the reserve base of fossil fuels) and the negative environmental aspects of the current transport system [1].

A persistent transition towards a more sustainable transportation sector will involve a mixture of several options such as: encouraging modal shifts (walking, cycling, and public transport), cleaner vehicle technologies, changing driving behavior, and controlling the need for motorized transportation [2].

A way to improve the environmental impact of the transport sector is by replacing old inefficient vehicles by newer ones. A passenger car in Belgium has a lifetime driven distance (LTDD) of 230,500 km, which corresponds to 13.7 years [3]. To cover this distance, a smaller impact on the environment could be obtained by replacing this car before its lifetime with an environmentally friendlier car. Vehicle replacement is normally driven by economic concerns. This paper gives insights in how to introduce environmental aspects in automobile replacement policies. These policies aim at accelerating the adoption of cleaner vehicles by taking old vehicles out of the fleet, while supporting the vehicle industry. On the other hand, a scrappage policy must take the whole life cycle of a vehicle into account. Scrapping an old vehicle and manufacturing a new one creates additional environmental impacts which must be taken into consideration. Results of a Life Cycle Assessment (LCA) will be used to check how the Belgian fleet can evolve towards a greener composition.

2 Methodology

Life Cycle Assessment is a cradle-to-grave approach to determine the total environmental impact of a product during its life cycle. It includes the extraction of raw materials, manufacturing, transportation, use and disposal. Since the 90s, LCA is a standardized methodology [4, 5]. It consists of four phases: goal definition and scoping, inventory analysis, impact assessment and interpretation.

The goal of this study is to adapt the vehicle fleet to a more ecological composition, in function of the LCA results. This analysis will be based on the comparison of the well-to-wheel emissions with the cradle-to-grave (manufacturing, dismantling, recycling and waste treatment) emissions for vehicles with different ages, Euro standards and technologies. Optimizing vehicle's LTDD causes an LCA challenge, combining two contradictory environmental engineering concepts. Letting a vehicle have a longer use phase avoids specific impacts during manufacturing, such as mineral extraction damage and energy usage. Product life extension is a well-known DfE (design for environment) strategy [6, 7]. To expand the LTDD the focus will lie on durability and maintenance. In this case the policy advice would be to replace the old vehicle as late as possible.

Conversely, replacement of an old vehicle with a new, more efficient one can lower the impacts introduced during the use phase. Depending on the level of benefit, the policy advice would be to replace the old car as soon as possible. In this case, the focus will lie on the development of cleaner vehicle technologies [8].

The optimal time to replace a car depends highly on the market availability of cleaner vehicles. If an optimization is to tackle greenhouse gases and there is no car on the market which consumes considerately less fuel, there is no reason to replace the old vehicle. Moreover, the CO_2 emissions introduced during scrapping an old car and manufacturing a new one would increase the overall impact on global warming.

To calculate in this case the optimal time of replacement [8] developed a methodology which takes future developments of cleaner vehicles into account. Today there are cleaner, energy efficient vehicle technologies available [9]. In this chapter it is discussed what can be done to optimize the environmental impact of a vehicle today. To differentiate between vehicle technologies it is investigated how long it takes a new car to have an environmental return on investment. If we replace an old car today, how fast are we going to feel the benefits? This period is the environmental breakeven point, the driven distance (or time) at which the investment of launching a new vehicle starts to have an environmental benefit.

The scope of the study is the Belgian family car fleet. A selection was made of comparable vehicles with different vehicle technologies. LCA seeks to compare the impacts of different products throughout their lifetime. A functional unit is used to have a comparable analysis. The chosen functional unit is the use of a passenger car in Belgium over a lifetime driven distance of 230,500 km corresponding to a vehicle lifespan of 13.7 years [3, 10]. In this assessment, Ecoinvent [11] default allocation criteria such as energy content, exergy, weight and unit price are always used for the background system.

After the Life Cycle Inventory (LCI), the different elementary flows, linked to a product system, will be translated into environmental impacts. This step is called Life Cycle Impact Assessment (LCIA). The LCIA starts with the selection of impact categories, the assignment of the elementary flows to the categories (classification) and the attribution the relative contribution of each elementary flow to a specific impact category (Characterization). Different environmental impacts are considered in this assessment: acidification [12], eutrophication [7], mineral extraction [13], energy [14], greenhouse effect [15] and respiratory effects of inorganics [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. Of course other impacts will have different results, but the aim is to develop a theoretical framework to deal with the environmental breakeven point.

3 Inventory

In this study, detailed environmental impacts of the different vehicle technologies are assessed for the small family car segment. A selection was made of comparable vehicles with different vehicle technologies. The Volkswagen Golf was used as a reference model as it is available since Euro 2 and is still a popular car on the Belgian market. When no VW Golf model was available, comparable cars have been chosen from the database. For the CNG technology, the Opel Zafira was used, for BEV the Nissan Leaf and for petrol hybrid the Toyota Prius. The Nissan Leaf is considered to have a Lithium battery of 300kg. The Toyota Prius has a NiMH battery of 56kg.

A far-reaching 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. No explicit cut-off criteria have been defined. Whenever possible, all vehicle materials and life cycle steps have been taken into account. The inventory is, in other words, a broad 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 [17]. 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.

3.1 Manufacturing

The LCI data of the 'Golf A4, 1,4l Otto' [18] used in the ecoinvent database [19] have been adapted to model the manufacturing phase of all vehicles with respect to their specific weights. For the hybrid and BEV, the LCI of the Golf A4 has been used to model only the body shell. Detailed LCI data of different battery technologies for hybrid electric (HEV) and battery electric vehicles (BEV) have been collected from the SUBAT project [20]. The manufacturing phase considered in this assessment contains material production, component production, assembly and transportation to the end-users.

3.2 Use phase

The use phase 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. Data concerning petrol, diesel and the Belgian electricity supply mix are gathered from the Ecoinvent database [11]. At the TTW side, the major part of the data is from the Ecoscore database [21]. It includes technology, weight, fuel consumption and homologation emissions of all the registered vehicles in Belgium.

Beside the homologation data, heavy metal emissions and non-exhaust particle emissions [22] are added to the TTW model. The maintenance phase is modeled as a part of the use phase to calculate the environmental breakeven point. This phase includes the tires, the washing water and the lead-acid battery and has been modeled with inputs from the LCI of the Golf A4 combined with assumptions from the IMPRO-CAR project [23].

4 Results

The overall LCA results for a full lifetime driven distance of 230,500 km is given in Table 1 for the different considered impact categories: mineral extraction and greenhouse effect. The manufacturing step is the key important life phase when considering damage to mineral resources. For this impact category, the size of a vehicle and the use of specific components requiring specific materials are the influencing parameters. The CNG vehicle has a larger impact because the considered vehicle is heavier than the other chosen vehicles. Hybrid vehicles have a higher impact for this indicator because of the use of specific and rare materials to produce components like the NiMH battery. The BEV has slightly lower mineral resource damage but the contribution of the 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. When dealing with climate impact, conventional vehicles have the highest impact. Diesel vehicles have a better score on this impact category than the respective petrol vehicles. A BEV powered with the Belgian supply mix electricity has a lower greenhouse effect than all the other vehicle technologies.

Table 1: Overview of total life cycle impact of the considered vehicle technologies.

TOTAL	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Mineral extraction damage [MJ]	2.02E +03	2.02E +03	2.20E +03	2.08E +03	2.69E +03	2.05E +03	2.35E +03	2.75E +03
Greenhouse effect [g CO_2 eq.]	6.43E +07	4.45E +07	4.77E +07	3.82E +07	3.98E +07	4.89E +07	3.04E +07	1.67E +07

Figure 1 gives an insight in the cumulative environmental burden of a specific vehicle. The first impact at zero driven distance is due to the manufacturing process. During the usage of a vehicle the cumulative environmental burden grows per kilometer. The negative values are avoided impacts due to the recovery of materials in the end-of-life (EoL) recycling step.

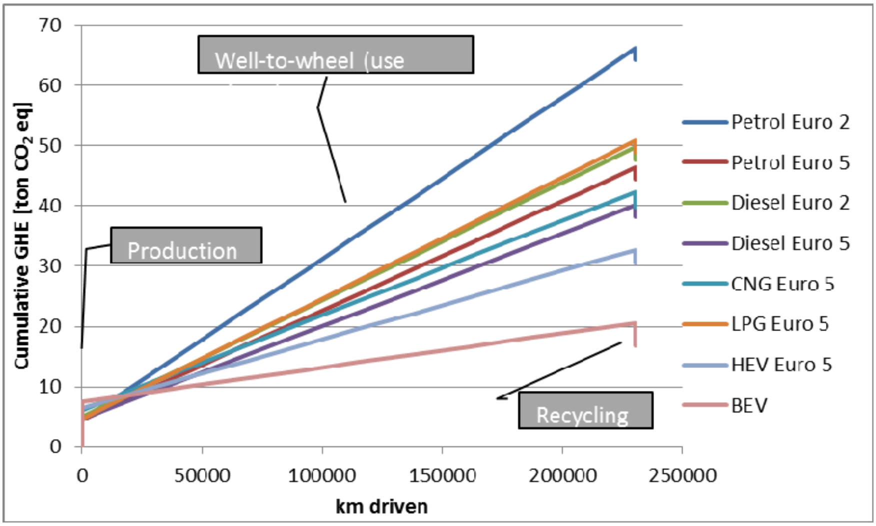

Figure 1: Cumulative burden on climate change for the different vehicle technologies.

The environmental breakeven point is introduced as the driven distance (or time) at which the investment producing a new vehicle starts to have an environmental benefit. The environmental breakeven point (D_b) will be dissimilar for each pair of cars and is shown in Figure 2. Each impact category will also give a different set of environmental breakeven points. To ease the decision on the replacement time, the different impact categories can be weighted in one single score. However, to stress the dissimilarity between the impact categories, a weighting factor is not taken into account in this paper. Figure 2 shows four possible choices when dealing with the replacement of a car.

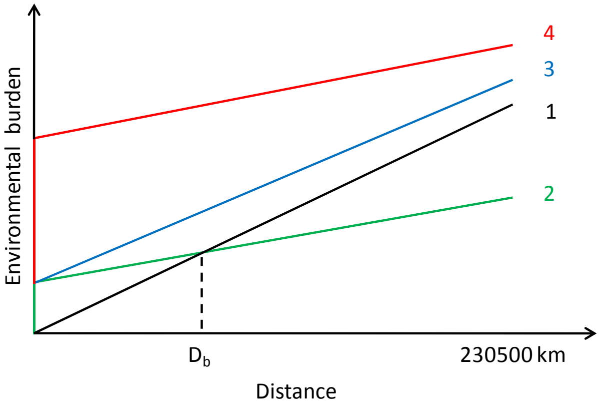

Figure 2: Environmental breakeven point of the replacement of a vehicle.

The environmental burden is shown in function of the time. At time zero the decision is made to replace the car or not. Line 1 (black) shows the cumulative environmental burden of the decision to keep on using the old vehicle. The old car was already manufactured, so the impacts during manufacturing are not changed by the decision. Therefore, the cumulative environmental burden of line 1 is only function of the maintenance and the well-to-wheel emissions. Line 2 represents the replacement with a cleaner vehicle, at distance D_b the environmental benefit of replacing the old vehicle starts. The offset of the environmental burden is due to the impact during manufacturing of the new vehicle, taking the end-of-life treatment and its negative (or avoided) impacts into account of the old vehicle. In situation 3 the benefit of use phase of the new vehicle is not big enough to have an environmental return on investment in an appropriate time frame. In situation 4 the impact of the manufacturing is too big to be compensated by the use phase, this is especially true when investigating impacts like mineral extraction damage.

The manufacturing of the old car is not allocated to the environmental burden of this car, as it is not influenced by the replacement decision. The transport, shredding and further separation processes the old vehicle are allocated to decision 2, 3 and 4. The End-of-Life (EoL) treatment is based on the state-of-the-art of the Belgian recycling activities [24].

The environmental breakeven point distance (D_b), described in Figure 2, can be calculated by expressing that the impact ($I_{no\ replacemen}t$, D_b) of decision 1 (no replacement) is the same as decision 2 (replacement after D_b km) and solving it for D_b. The environmental burden for the "no replacement" scenario at distance D_b is given by equation (1).

$$I_{no\ replacement,Db} = D_b \cdot i_{Use\ vehicle\ 1} \tag{1}$$

The environmental burden for the "replacement" scenario at distance D_b is given by equation (2).

$$I_{replacement,Db} = I_{EoL\ vehicle\ 1} + I_{Man.\ vehicle\ 2} + D_b \cdot i_{Use\ vehicle\ 2} \tag{2}$$

with:

$I_{no\ replacement,\ Db}$:	Impact for the scenario "no replacement" after D_b km"
$I_{replacement,\ Db}$:	Impact for the scenario "replacement" after D_b km
D_b:	Environmental breakeven point, expressed in km
$i_{Use,\ vehicle\ j}$:	Impact per km on the use phase (Well-to-wheel and maintenance) of vehicle j
$I_{Man,\ vehicle\ j}$:	Impact of the manufacturing phase of vehicle j
$I_{EoL,\ vehicle\ j}$:	Impact of the End-of-life treatment phase of vehicle j

The environmental breakeven point can be calculated with equation (3).

$$D_b = \frac{I_{EoL,\ vehicle1} + I_{Man,\ vehicle2}}{i_{Use,\ vehicle1} - i_{Use,\ vehicle2}}\ km \tag{3}$$

www.witpress.com, ISSN 1743-3509 (on-line)

The detailed information of the breakeven points for climate change is given in Table 2. The environmental breakeven points are given for the replacement of a vehicle in column i with vehicle in row j. Only positive values are withheld.

Table 2: Environmental breakeven point for the greenhouse effect when replacing a vehicle in column i with vehicle in row j, expressed in kilometres.

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Petrol Euro 2	-	-	-	-	-	-	-	-
Petrol Euro 5	**3.11 E+04**	-	**1.91 E+04**	-	-	**1.37 E+04**	-	-
Diesel Euro 2	**4.25 E+04**	-	-	-	-	508,445	-	-
Diesel Euro 5	**2.51 E+04**	**1.01 E+05**	**6.51 E+04**	-	6.21 E+05	**5.96 E+04**	-	-
CNG Euro 4	**3.90 E+04**	**1.76 E+05**	**1.10 E+05**	-	-	**9.80 E+04**	-	-
LPG Euro 4	**4.16 E+04**	-	-	-	-	-	-	-
HEV Euro 5	**3.01 E+04**	**6.82 E+04**	**5.50 E+04**	**1.14 E+05**	**9.10 E+04**	**5.27 E+04**	-	-
BEV	**2.70 E+04**	**4.55 E+04**	**3.99 E+04**	**5.77 E+04**	**4.98 E+04**	**3.91 E+04**	**9.17 E+04**	-

Table 3: Environmental breakeven point for mineral extraction damage when replacing a vehicle in column i with vehicle in row j, expressed in kilometres.

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 4	LPG Euro 4	HEV Euro 5	BEV
Petrol Euro 2	-	-	-	-	-	-	-	7.15 E+05
Petrol Euro 5	1.73 E+07	-	-	-	-	-	-	6.96 E+05
Diesel Euro 2	1.34 E+07	4.50 E+07	-	-	-	-	-	7.62 E+05
Diesel Euro 5	9.96 E+06	2.21 E+07	4.57 E+07	-	-	-	-	7.04 E+05
CNG Euro 4	1.04 E+07	1.84 E+07	2.70 E+07	4.86 E+07	-	5.10 E+07	4.60 E+07	9.43 E+05
LPG Euro 4	9.69 E+06	2.12 E+07	4.25 E+07	7.79 E+08	-	-	-	6.92 E+07
HEV Euro 5	1.26 E+07	2.74 E+07	5.43 E+07	6.81 E+08	-	2.04 E+09	-	9.25 E+07
BEV	-	-	-	-	-	-	-	-

Values higher than the total lifetime driven distance (230,500 km) are not in bold, since a higher value means that the replacement will have no positive effect during the vehicles' lifetime. For instance, in column 4 the breakeven points for replacing a diesel Euro 2 vehicle with another vehicle technology are given. Replacing a diesel Euro 2 vehicle with a diesel Euro 5 vehicle will have a benefit on the GHE after 65,000 kilometers. Each impact category will also give a different set of environmental breakeven points, all impact categories and their corresponding sets of breakeven points are given in Table 2.

5 Conclusions

The environmental breakeven point is introduced as the driven distance (or time) at which the investment of launching a new vehicle starts to have an environmental benefit. The environmental breakeven point will be dissimilar for each pair of cars. A methodology and data is provided to calculate the environmental breakeven point for different types of vehicle technologies and impact categories. The considered electric vehicle has the lowest impact on climate change and consequently it can replace every considered car when dealing with this impact category and have a positive effect after a distance ranging from 27,000 km (when replacing a Petrol Euro 2 vehicle) to 91,000 km (when replacing a fuel efficient hybrid Euro 5 vehicle). It is clear that in this situation the environmental breakeven point falls in the Life Time Driven Distance of 230,500 km (average life time of a vehicle in Belgium). Hybrid vehicles can replace all other technologies (except BEV) and still have a positive influence before the end-of-life. When introducing automobile replacement policies in order to accelerate the adoption of cleaner vehicles by taking old vehicles out of the fleet, one must bear in mind that such a scrappage policy is focusing on reducing environmental impacts introduced during the use phase. The policy advice would be to replace the old vehicle as soon as possible with a cleaner vehicle technology in order to maximize the environmental benefits. Conversely, letting a vehicle have a longer use phase avoids specific impacts during manufacturing, such as mineral extraction damage. It is clear that the replacement of a vehicle cannot have a positive effect on this impact category, as the manufacturing of a new vehicle will always introduces mineral usage and depletion. Letting a vehicle have a longer use phase avoids this specific impact. To expand the LTDD the focus will lie on durability and maintenance. In this case the policy advice would be to replace the old vehicle as late as possible.

Acknowledgements

This research has been made possible thanks to the support and funding of the Belgian Science Policy (BELSPO) 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 [25].

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