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The environmental potential of an electric vehicle with an in-life modular range extension

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Executive Summary

Purpose: The range of an electric vehicle (EV) remains an important hurdle for the consumer market to adopt the technology. Opting for an EV with an over-dimensioned not only significantly increases the capital and operational expenditure, it also creates a substantial burden to the vehicle's climate change impact. Covering the marginal utility of the EV by means of a range extender-equipped trailer on those days when extra range is needed, is investigated for feasibility in this paper.

Method: A life cycle assessment (LCA) is performed, considering the manufacturing, use and eventual disposal of the EP Tender. A benchmark comparison is presented for the combination of a 40 kWh EV coupled to an EP Tender and a range of conventional cars and EVs, differentiated by their battery capacity.

Results and discussion: Assuming a marginal utility factor which equals 5% of the yearly driven distance by car, the 40 kWh EV+EP Tender combination performs quite similar to a 60 kWh EV when it comes to the impact on climate change. The difference with the latter EV is that for 95% of the time no extra battery weight is to be moved by the 40 kWh EV. Compared to the 90 kWh EV, the impact is reduced by a third.

Conclusion: In terms of their impact on climate change, all discussed EVs were found to contribute significantly less than the ICE-based technologies. Over-dimensioned EVs might allow the higher-end consumers a shift towards electro mobility, but in reality cause a substantially higher environmental burden. The investigated alternative of covering the marginal utility by means of a range extender is proven in this paper to be environmentally more sustainable.

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1. Introduction

1.1. Context

Since the Industrial Revolution, anthropogenic activities have led to a steady increase in atmospheric carbon dioxide (CO_2) concentrations [1], [2]. This situation has escalated to such an extent since the second half of

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[1] VUB-MOBI Group is a member of Flanders Make

the last century, that the maximum concentration which was deemed sustainable (400 parts per million (ppm)) had been surpassed for the first time in 2013. Therefore, 195 nations worldwide agreed to keep the average global temperature increase well below 2°C, i.e. by 2015 Paris Agreement [3]. Next to the imminent threat of climate change, virtually every European city is plagued by air quality levels deemed harmful to human health [4]. Diesel-based road transport, of which the emissions are found carcinogenic by the World Health Organisation (WHO)[5], have an important contribution to this issue. Battery electric vehicles (EV) offer a less polluting solution for our current personal mobility system, as they produce no exhaust gas emission during use. *Less* polluting, as non-exhaust particulate matter (PM) emissions due to brake, tire and road wear are independent of powertrain choice [6]. According to the current European regulations, emissions from passenger cars are based solely on the tank-to-wheel (TTW) contribution [7]. In the light of reducing the passenger car sector's impact on climate change, car manufacturers are imposed by the European Commission to obtain a corporate average fuel economy (i.e. TTW) which was capped at 130 g/km by 2015 and is to be reduced to 95 g/km by 2021 [8]. Therefore, the electrification of powertrains has taken off since the last decade. Stimuli for manufacturers consisted of so-called *super-credit factors,* by means of which vehicles with CO_2 emissions below 50 g/km were counted as more than one vehicle in the corporate average. The first phase of this approach lasted until 2016, while it will be repeated from 2020 to 2023 [9]. This concession for electrified powertrains induced national and regional incentive schemes to roll-out both EV and plug-in hybrid electric vehicles (PHEV). Due to an unrealistic type-approval procedure comprising of a driving simulation known as the New European Driving Cycle (NEDC), PHEVs were falsely accredited their super-credits as their real-world driving emissions for CO_2 (RDE) were found to be up to three times their certified emission factors, on average [10]–[13]. This raises the question whether PHEVs will be the dominant powertrain topology for reaching post-2021 CO_2 targets.

When EVs are compared to conventional (internal combustion engine-based, ICE) powertrain technologies, it makes no sense to cover only tank-to-wheel emissions (TTW), as indirect emissions upstream the energy carrier supply chain add to climate change as well. These are referred to as well-to-tank (WTT) emissions. The European TTW-bias in favour for EVs is however confirmed when both direct and indirect emissions are considered, i.e. in a well-to-wheel emissions (WTW) approach. By doing so, a level playing field is created for comparing technologies. For EVs to outperform other powertrain types to their full potential, the energy production is required to be as sustainable as possible. Whereas the electricity production based on fossil fuels is found to bring an EV's impact on climate change to similar or worse levels than for conventional technologies, electricity from wind or solar power could reduce an EV's impact to fractions of the ICE car's [14]. In the light of the Paris Agreement, EVs are seen as key assets to decarbonise the existing passenger car sector. Therefore, the scope of this paper is set on the impact on climate change. What exceeds the scope is the EV's impact on local air quality, although earlier work by the authors of this paper revealed the advantage of electric mobility in urban settings [6].

Despite the advantages EVs offer, the market uptake remains below expectations, indicated by a 2016 EV sales share below 0,5% [15]. Nonetheless, economy of scales due to worldwide sales on one hand and financial incentivization by national and regional governments on the other hand, have made EVs a worthy alternative for the conventional car. Whereas top-end manufacturers offer theoretical electric ranges up to 500-600 km [2], more affordable mid-class cars can cover a theoretical range typically exceeding 250 km. Theoretically, as both driving style and exogenous conditions such as local climate and traffic characteristics influence the effective range.

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[2] Based on the New European Driving Cycle (NEDC) and thus an overestimation of the realistic range

1.2. Range anxiety

Despite reasonable EV ranges, it still is up to the 'early adopters' to pave the way for a broad market uptake, while local governments and private companies urge to roll-out a charging network. This is needed and has been proven to relieve the so-called 'range-anxiety' which continues to haunt the potential EV buyer [16]. The phenomenon of range anxiety originates from a lack of hands-on experience and is found to decrease as more electric kilometres are performed [17][18]. In addition, range-anxiety is countered by travel statistics, as the average daily driven distances for passenger cars ranges from 40 km to 80 km, based on a 2012 mobility survey by the European Commission's Joint Research Centre (JRC) for six European Member States [19]. A recent American study indicated that the 87% of a large-scale test group's vehicle days were successfully performable with a 24 kilowatt-hour (kWh) electric vehicle. If a 40 kWh battery is assumed to become the reference on the short-term, the study's results indicate approximately 95% of the vehicle days could be covered electrically. Nevertheless, the average consumer tends to stick to a technology which offers a worriless range exceeding 800 km, albeit at the cost of a dramatic fuel efficiency, poor air quality and a significant climate change impact. This mentioned technology is based on internal combustion engines (ICE).

Figure 1: the combination of a Renault Zoe and the EP Tender trailer [20]

1.3. EP Tender

To ramp up the interest in electromobility, charging infrastructure providers and car manufacturers are planning to create fast-charging corridors across Europe, which would allow to long-distance travel with EVs [21]. Such a network would nevertheless put a serious burden the electric grid and would require a substantial investment. A more pragmatic way for covering the 5% of the time when longer ranges are needed is the EP Tender, as presented in Figure 1. This shared trailer system consists of a generator and hereby a mean to extend an EV's trip with roughly 300 km. The principle behind this range-extender is that it allows an EV user to cover *all* its trip requirements, including the few percentages of time when long distances need to be covered, referred to as the marginal utility. The general idea behind this concept is that it's both economically and environmentally unreasonable to oversize the battery or to pay for a fixed range extender whereas a 40 kWh battery pack could cover 95% of the trips.

2. Environmental impact assessment

2.1. Goals and scope

The objective of this paper is to present an analysis on the environmental impact for a range of mid-sized family cars, characterized by different powertrains. A life cycle assessment (LCA) is performed to evaluate the impact on climate change of a range of ICE-based powertrain technologies, as well as a set of EVs and the combination of an EV and the EP Tender. With the aim of proving that an over-dimensioned battery pack has a negative environmental impact, one high-end EV with a battery pack capacity of 90 kWh was added to the vehicles list as well. The scope of this investigation focusses on the European market and power production mix. This is assumed to have an average CO_2 emission intensity of 276 grams per kWh of electricity produced [22].

As the discussed vehicles have the function to provide mobility, the functional unit is driving one kilometre. A total driven distance at the end-of-life of 209.460 km is assumed, prior to recycling of the vehicle. The system boundaries are shown graphically in Figure 2 and comprise the complete life cycle of the product, in this case the different passenger cars.

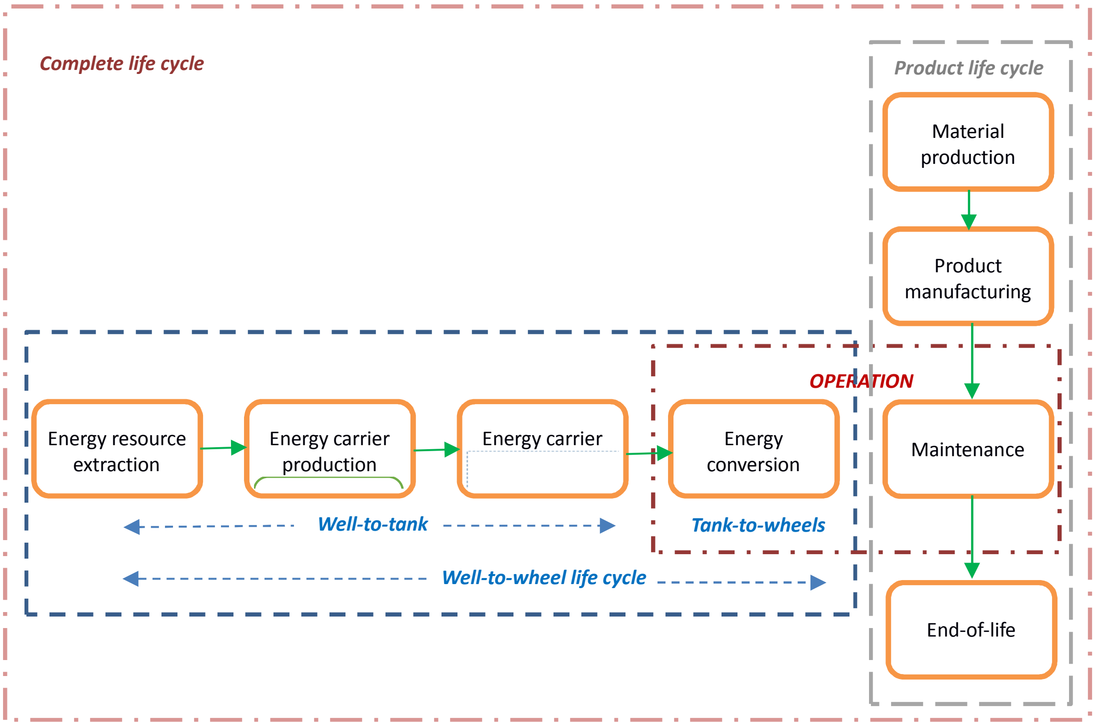

Figure 2: LCA system boundaries

3. Methodology

3.1. A range-based life cycle assessment

An environmental LCA is used to compare the impacts, damages and benefits of the different powertrain technologies while considering all the associated emissions, both direct and indirect. This process considers a Life Cycle Inventory (LCI) of every emission and raw materials used throughout the different product stages, as shown in Figure 2. The advantage of separating the different product life stages enables the identification of the causes of specific impacts and emissions per stage in the product's value-chain [6]. The selected impact assessment methodology which was applied in the SimaPro 8.3 software is ReCiPe midpoint (H) [23]. Out of a set of 18 midpoint impact categories, the focus is climate change and hence the emission of greenhouse gasses (GHG). Midpoint indicators serve as an intermediate between the emission source and the 'endpoint', representing the recipients of the environmental effects caused by anthropogenic activities, as there are Human Health, Ecosystem Quality and Natural Resources [24]. No endpoint indicators are discussed in this paper.

For the comparison of the different technologies, a range-based approach was chosen, based on Messagie *et al* [25]. This methodology allows to distinguish the different impacts per technology per functional unit, in this case one kilometre driven. The entire life cycle impact is calculated by considering the earlier mentioned lifespan of 209.460 km. Concerning the use phase impacts, an update of the official TTW emission factors was performed to reflect real-world driving emissions (RDE), based upon Hooftman *et al* [6]. The reason hereto is that the European type-approval process, based upon the New

European Driving Cycle (NEDC), significantly underestimates both the emissions of greenhouse gasses and toxic pollutants [37][38].

3.2. Assumptions

For the comparison of the EV+EP Tender combination with the other technologies, the marginal utility covered by the trailer is assumed to be 5% of the vehicle's lifetime driven distance. Moreover, one EP Tender is assumed to be shared by 15 users, meaning that its manufacturing impact is consequently shared over these 15 users. For the remaining 95% of the EV's lifetime, it is assumed to drive purely electric whilst charging with the European electricity mix, characterised by a CO_2 emission intensity of 276 g per kWh produced [22]. Equation 1 shows how the EV's well-to-tank emission during 95% of the time are based on the EV's average consumption (kWh/km), while the EP Tender is assumed to be applied specifically for covering long distances over highways. Moreover, the EV's highway consumption is assumed to be influenced by the trailer's weight, as an extra consumption of 5% is applied in case the trailer is towed highway speeds. The consumption data of the different EVs can be seen in Table 1. Notice that both the average and highway consumption rates are identical for the presented EV technologies below 90 kWh and refer to official testing by the US Department of Energy [28]. The specifications for the trailer are given in Table 2. The fuel consumption specifications of the conventional cars are given in Table 3. The remainder of this paper, the EP Tender is assumed to be towed by a 40 kWh EV.

$$WTT_{EV40+EP\ Tender} = \left(0{,}95 \times WTT_{EV40,avg}\right) + \left(0{,}05 \times \left(WTT_{EV40,highway} + WTT_{EP\ Tender}\right)\right) \quad \text{Equation 1}$$

Table 1: Specifications of the discussed electric vehicles (based upon [28])

Parameter [unit]	30 kWh EV	40 kWh EV	60 kWh EV	90 kWh EV
Capacity [kWh]	30	40	60	90
Mass in Running Order [kg]	1591	1450	1624	2200
Weight battery [kg]	272	305	435	540
Average consumption [kWh/km]	0,15	0,15	0,15	0,25
Highway consumption [kWh/km]	0,20	0,20	0,20	0,26
Highway consumption with EP Tender [kWh/km]	0,210	0,210	0,210	0,273

Table 2: Overview of the EP Tender characteristics

EP Tender	
Rated power [kW]	25
Mass [kg]	265
Fuel tank [l]	35
Fuel type	Petrol
Range [km]	300
Average consumption [l/kWh]	0,44
Average consumption [l/100 km]	7,5

Table 3: Overview of the fuel consumption indicators per technology

Unit	Petrol	Petrol hybrid	Diesel	Plug-in electric vehicle
[l/100 km]	6,8	5,6	5,3	3,4

4. Life cycle inventory

Based upon a life cycle inventory (LCI), the elementary flows which are linked to the various vehicle technologies need to be converted to the different impact categories. These allow a quantification and a comparison between the potential impacts. This step is referred to as the lifecycle impact assessment (LCIA)[6]. Concerning the environmental performance of the EP Tender itself, the product's LCI was developed by means of a bill of materials provided by the manufacturer and the homologation certificate for the regulated emissions [29]. The emission factors obtained from the homologation certificate are given in Table 4.

Table 4: Certified emission factors for the EP Tender [29]

Unit	Average generator emissions				
	HC	CO	NO_x	CO_2	$HC+NO_x$
[g/kWh]	2,525	40,485	1,099	999,406	3,624

Concerning the impact of manufacturing the EP Tender trailer, a deliberate distinction was made between the production of the 'trailer body' and the production of the generator set, while the operation of the latter was analysed during its use phase. This choice was made to allow a better insight in the allocation of their respective contribution to different midpoint indicators (in this case: climate change). The total lifetime of the trailer was chosen to be identical to that of a passenger car itself, namely 209.470 km. An overview of the manufacturing impact is presented in Table 7 in the appendix. The eventual impact per kilometre driven for combination of the 40 kWh EV + EP Tender is given in Table 5. Keep in mind that in the remainder of this paper, the impacts of the trailer's assembly for both the bodyworks and the generator are divided by 15, as the product is developed to be shared by the same number of users. Notice that the European electricity mix is included, representing the 95% of the time during which the EP Tender is decoupled from the EV. The fact that the EP Tender has a significant impact for being active only 5% of the time emphasizes the potential environmental improvements if the generator would be substituted by a fuel cell or a battery pack.

Table 5: Overview of the impact of one EP Tender trailer on climate change

Impact category	Unit	Total	Trailer Assembly excl. generator	Generator manufacturing	Generator operation	European electricity mix EV 40 kWh
Climate change	kg CO_2-eq./km	1,09E-01	2,12E-03	3,67E-03	1,27E-02	9,09E-02

Based upon Messagie *et al,* the different technologies are compared for their well-to-tank and tank-to-wheel emissions, while the impacts on climate change from the powertrain and vehicle cycle are included as well [25].. These four parameters cluster a list of different sub-parameters, as can be seen in an exemplary LCI of a 30 kWh EV, as shown in Table 8 in the appendix. The summary of the impacts per kilometre for the different vehicles on climate change is presented in Table 6.

Table 6: Summary of the LCI for the various powertrain technologies concerning climate change

CC [kg CO_2-eq./km]	WTT	TTW	Vehicle cycle	Powertrain cycle	Total
Petrol Euro 6	3,80E-02	1,63E-01	1,23E-02	2,65E-03	2,16E-01
Diesel Euro 6	2,33E-02	1,42E-01	1,28E-02	2,65E-03	1,81E-01
Hybrid Euro 6	2,95E-02	1,35E-01	1,55E-02	6,72E-03	1,87E-01
Plug-in Hybrid Euro 6	7,42E-02	8,08E-02	1,76E-02	1,24E-02	1,85E-01
30 kWh EV	4,17E-02	0,00E+00	1,46E-02	1,59E-02	7,22E-02
40 kWh EV	4,17E-02	0,00E+00	1,35E-02	2,00E-02	7,52E-02
60 kWh EV	4,17E-02	0,00E+00	1,49E-02	2,83E-02	8,49E-02
90 kWh EV	6,93E-02	0,00E+00	1,96E-02	4,08E-02	1,30E-01
40 kWh EV + EP Tender	4,15E-02	1,27E-02	1,36E-02	2,03E-02	9,86E-02

5. Results

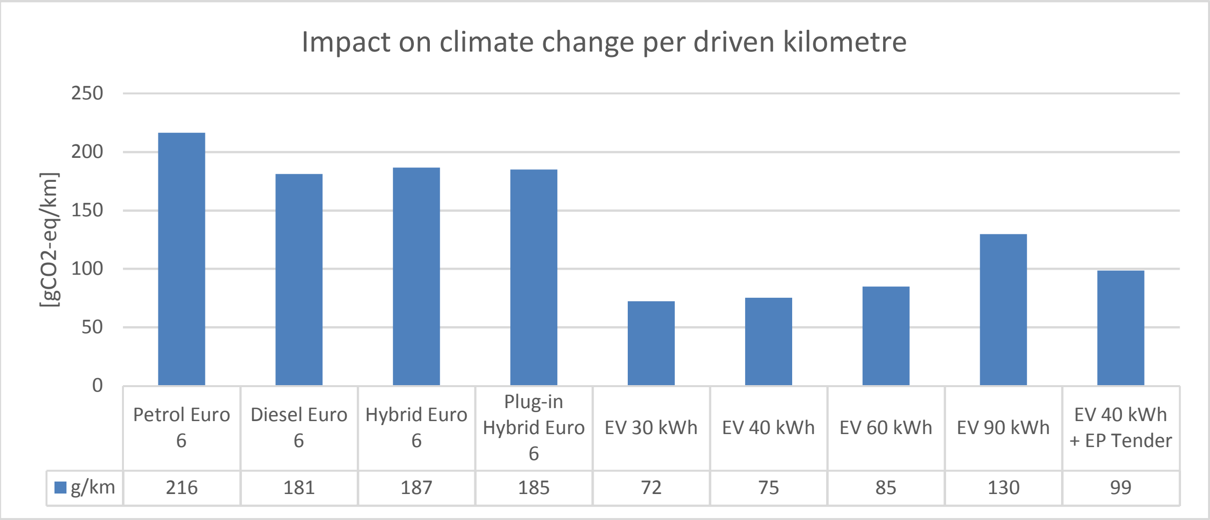

Figure 3: Impact on climate change for the different powertrain technologies

The impact on climate change for the given powertrain technologies is shown in Figure 3.The LCA approach shows that EVs in general have a lower impact than ICE based vehicles. Notice that a focus on the TTW approach only, as applied by the European Commission, emphasises the advantage for EVs on the one hand and PHEVs on the other hand, despite RDE emission factors. An LCA approach however, considers all related direct and indirect emissions. Thus, PHEVs have similar impact as the other ICE powertrains, except for petrol cars. The latter technology typically remains consuming more fuel per kilometre, which is reflected by the highest TTW share. As the PHEV consumes both petrol and electricity, its WTT share is considerably bigger than for the other ICE cars, as well as for the presented EVs. Comparing the electric powertrain, the bigger the battery pack is designed, the higher it's impact becomes on climate change. This effect is reported in an increasing trend from hybrids onwards. Consequently, the 90 kWh EV has the biggest powertrain cycle impact and hereby also the highest WTT share. The WTT share for EVs in general reflects the European electricity production mix and indicates the potential of renewable energy sources, as they could virtually reduce the WTT impact to fractions of what presented in this exercise.

Whereas the combination of the 40 kWh EV and the EP Tender trailer represents a range which equals the discussed 90 kWh, a one-on-one comparison of the two clearly indicates the advantage of modular solution. As it is presented here, attaching the EP Tender occasionally to a 40kWh EV has a similar impact than upgrading the car from 40kWh to 60 kWh EV. Moreover, other combinations with the EP Tender can be made as well, depending on the mobility needs of the EV user.

6. Conclusion

In the presented paper, the impact per kilometre is given for a set of powertrain technologies. In general, EVs are found to contribute considerably less to climate change, even when the entire life cycle is assessed. Following the specific contributions generated during the well-to-tank phase, the potential of renewable electricity is indicated. In this case, the well-to-tank contribution could virtually be reduced to fractions of what is reached in this exercise, thereby increasing the difference with the conventional technologies. Specific attention went to the 90 kWh EV and a combination of the 40 kWh EV and a range extender generator, i.e. the EP Tender. Whereas the former represents an impact of approximately 150 g/km, the latter allows to bring down this impact with one third, to nearly 100 g/km. This indicates the potential of modular range extension for EVs, while most of the daily trips are covered purely electric with a reasonably sized battery pack. This is to the advantage of the user on the one hand by means of the capital expenditure for an electric vehicle and the operational cost of it, on the other hand. Although there is no doubt that electric vehicles will play an important role in the framework of the Paris Agreement, a broad-scale market uptake requires potential users to understand that limited ranges do not necessarily have to limit mobility. Range extender concepts as presented in this paper offer more sustainable (and affordable) solutions than over-dimensioned EVs, when their battery capacity is considered. This sustainability could be further increased by both replacing the petrol generator by a battery pack/fuel cell and by placing the focus for energy production on renewable sources.

Acknowledgements

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Appendix

Table 7: Impact on climate change for producing the EP Tender trailer, consisting of the bodyworks and the generator

BODYWORKS	*kg CO2 eq*	GENERATOR	*kg CO2 eq*
Chassis	6,83E+01	Metal working, aluminium	1,57E+02
Jockey Wheel	4,84E+00	Copper	1,99E+01
Sec. Wheel Ass.	6,81E+01	Metal working, steel	7,84E+01
Main Wheel Ass.	2,32E+02	Electronic control unit	2,67E+01
Shock Absorber	3,43E+01	Aluminium	1,65E+02
Sundries	1,16E+01	Polyethylene	1,93E+01
12V Motor	1,23E+01	Steel	7,74E+01
Junction Box	3,63E+01	Batteries	1,42E+01
Bodywork	1,73E+02	Polybutadiene	9,97E+00
Cat. Converter	1,00E+01	Aluminium alloy, AlMg3	3,91E+01
Generator	7,69E+02	Recycling	1,63E+02
Total	6,50E+02	Total	7,69E+02

Table 8: LCI of a 30 kWh EV for the European electricity mix (276 gCO$_2$/kWh) (based on [25][30])

Midpoint	**WTT**		**TTW**				**Vehicle cycle**			**Powertrain cycle**							
	WTT	**Public charging station**	**Tire abrasion**	**Road abrasion**	**Brake abrasion**	**TTW**	**Body shell**	**Lead battery**	**Maintenance**	**Li battery**	**Electric Motor**	**AC/DC converter**	**DC/DC converter**	**On-board charger**	**Catalytic converter**	**Starter and generator**	**Engine Control Unit**
CC [kgCO$_2$/km]	4,14E-02	2,95E-04	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,30E-02	6,29E-05	1,52E-03	1,24E-02	1,19E-03	1,35E-03	5,08E-04	4,14E-04	0,00E+00	0,00E+00	0,00E+00
POF [kgNMVOC/km]	2,68E-05	7,42E-07	0,00E+00	0,00E+00	0,00E+00	0,00E+00	4,08E-05	2,56E-07	4,94E-06	4,54E-05	4,68E-06	5,66E-06	1,99E-06	1,98E-06	0,00E+00	0,00E+00	0,00E+00
PMF [kgPM$_{10}$/km]	5,83E-06	4,51E-07	7,05E-06	1,00E-05	2,46E-06	0,00E+00	3,12E-05	1,91E-07	2,46E-06	3,16E-05	4,77E-06	3,21E-06	1,19E-06	1,07E-06	0,00E+00	0,00E+00	0,00E+00
HT [kg1,4-DB/km]	2,03E-04	4,43E-04	6,37E-04	4,01E-06	7,35E-04	0,00E+00	1,34E-02	3,03E-04	5,86E-04	8,22E-03	5,72E-03	6,12E-03	2,31E-03	1,97E-03	0,00E+00	0,00E+00	0,00E+00

Authors

Nils Hooftman is an engineer who joined the ETEC team in 2012 as an associate in the research group MOBI – Mobility, Logistics and Automotive technology (Vrije Universiteit Brussel) led by Prof. Dr. Ir. Joeri Van Mierlo. His PhD work focuses on real-world vehicle emissions. In the first part of his PhD, Nils worked behalf of the AIBV, one of the Belgian private organizations responsible for the periodical technical inspection of road vehicles. This project implied the improvement of the current inspection program. Currently Nils works under the supervision of prof. Thierry Coosemans on the uptake of EVs in Europe and its consequences in terms of climate change and local air quality.

Dr. Maarten Messagie is an engineer specialized in industrial development, he also obtained a Master degree in sustainable development (VUB) and specialized himself in environmental assessment methodologies as trainee in an environmental consultancy agency and as PhD student in Aalborg University and the University of Trondheim (NTNU). Currently he is an environmental researcher for the MOBI team working on environmental assessments (Well-to-Wheel and Life Cycle Assessment) of the transport and energy sector in various national and international projects. His main focus is on conventional and alternative vehicles, with a special interest for electric and hybrid cars. His research interests are alternative vehicle technologies, Life Cycle Assessment methodology, ecodesign and sustainable energy systems.

Jean-Baptiste Segard graduated from the Swiss Federal Institute of Technology in Lausanne (EPFL). He received the Maillefert award for research and creativity. He founded EP Tender in 2012 from his own frustration of willing to purchase an EV, but having to renounce due to rare occasional long distance trips (he now drives an EV!). He was previously a senior executive in the asset management industry.

Frédéric Joint graduated from INSA Lyon in 2016. Interested by energy issues in transportation, he joined EP Tender as a development engineer. He has a background on LCA evaluating impacts for cement industrial processes.

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Prof. Dr. ir. Joeri Van Mierlo leads the MOBI – Mobility, Logistics and automotive technology research centre (http://mobi.vub.ac.be). A multidisciplinary and growing team of 70 staff members. He is expert in the field of Electric and Hybrid vehicles (batteries, power converters, energy management simulations) as well as to the environmental and economical comparison of vehicles with different drive trains and fuels (LCA, TCO).

Prof. Van Mierlo was Vice-president of AVERE (2011-2014)(www.avere.org), the European Electric Vehicle Association and board member its Belgian section ASBE (www.asbe.be). He chairs the EPE chapter "Hybrid and electric vehicles" (www.epe-association.org). He is an active member of EARPA (European Automotive Research Partner Association) and member of EGVIA (European Green Vehicle Initiative Association). He is member of the board of Environmental & Energy

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