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Reducing the environmental impacts of passenger cars: a comparison between electricity and biofuels

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Abstract

This study assessed the potential for decreasing the environmental impact of the European road transport sector by exploiting biofuels. After processing available data on the actual trends of biofuels utilisation in the sector, laboratory and on-road tests were conducted to compare the emissions from a C-segment Euro 6d-TEMP passenger car fed with commercial reference petrol and three experimental petrol blends containing components of renewable origin. Through the Life Cycle Assessment methodology based on measurement data, the environmental impacts of the four fuels were compared with an average C-segment battery electric vehicle. Concerning a fossil petrol car, all the fuels slightly reduced the impact on climate change, while the battery electric vehicle performed best. For the remaining environmental impact categories, the picture was less straightforward.

Keywords: Life Cycle Assessment; biofuels; electric vehicles; alternative powertrains; e-fuels; well-to-wheels analysis.

1. Introduction

Road transport plays a critical role in air pollution and anthropogenic global warming. Electric mobility development is progressively and widely identified as the most effective way to reduce road transport contribution to local air pollution and climate change. Still, the complete substitution of the internal combustion engine vehicles (ICEVs) is not likely to be achieved in a short time, making it necessary to find solutions to decrease their environmental impact progressively. This study addressed the potential of alternative biofuels utilization, with respect

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to conventional fossil feed mixtures, for reducing the general environmental impact of the European road transport sector. Following a literature review and data processing for assessing the current state and perspective potentials of biofuels in Europe for road transport, laboratory and on-road tests were conducted to compare the emissions from a Euro 6d-TEMP GDI passenger car fuelled with a baseline commercial reference petrol and three experimental petrol blends containing different components of renewable origin. The resulting data were used as input for a Life Cycle Assessment (LCA) study, where the potential environmental impacts of the four fuels in ICEV were compared with those derived for an average C-segment battery electric vehicle (BEV).

Nomenclature

BEV	battery electric vehicle
ETBE	ethyl tert-butyl ether
EtOH	ethanol
GDI	gasoline direct injection
GHG	greenhouse gas
HC	hydrocarbons
HVO	hydrotreated vegetable oil
ICEV	internal combustion engine vehicle
LUC	land use change
ISO	International Organization for Standardization
LCA	life cycle assessment
NMHC	non-methane hydrocarbons
NMVOC	non-methane volatile organic compound
PEMS	portable emissions measurement system
PM	particulate matter
PM	particles number
RDE	real driving emissions
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WTW	well-to-wheels

2. Materials and methods

The literature review investigated what types of biofuels are currently available for road transport, how they can be produced in terms of processes and feedstocks, what the current state of biofuels for road transport in Europe is, and what the most recent LCA studies tell us about the well-to-wheels (WTW) environmental impact of the use of biofuels in light-duty vehicles in Europe. In particular, the literature review about LCA studies covered 86 scientific articles issued from 2013 to 2020, in addition to other publications and case studies from the grey literature, identified via backward snowballing.

The experimental part of the research consisted in testing a Euro 6d-TEMP GDI passenger car with four different fuels both in the laboratory and on the road. The exhaust emissions of three experimental petrol blends (Fuel B, C, and D) were measured to evaluate their conformity to the Euro 6 standards and to compare them with those released using commercial reference petrol (Fuel A), containing 3.6% v/v of bio-ETBE (ethyl-tertiary-butyl ether). Simplified composition data for the reference fuel and the experimental blends are reported in Table 1.

Table 1. Simplified composition of the evaluated test fuels.

Fuel	Unit of measurement	Fuel A	Fuel B	Fuel C	Fuel D
Petrol	% v/v	96.37	84.94	78.21	92.49
Bio-ETBE	% v/v	3.63	-	21.79	-
Bionaphtha	% v/v	-	7.0	-	-
Bioethanol	% v/v	-	8.06	-	4.80
Methanol (potentially biomethanol or e-methanol)	% v/v	-	-	-	2.71

The exhaust emission measurements included regulated and non-regulated pollutants, as well as greenhouse gases (GHGs). Laboratory tests were carried out by driving the ICEV on a chassis dynamometer, following the European homologation cold-start WLTC (Worldwide harmonized Light vehicles Test Cycle) (European Commission, 2017a).

The chassis dynamometer, placed inside a climatically controlled test cell, simulates road conditions and allows repeatable and reproducible testing. The test is characterised by a duration of 30 minutes and a distance of 23.25 km.

The WLTC simulates typical driving conditions and is subdivided into phases with different speed ranges: Low, Middle, High, and Extra-High. The on-road tests were developed and driven in compliance with RDE (Real Driving Emission) regulation (European Commission, 2018, 2017b, 2016a, 2016b). The car was driven for 90-120 minutes on different types of public roads: urban roads (low speed), rural roads (medium speed), and motorways (high speed).

Comparisons among the three innovative blends and the reference Fuel A were evaluated regarding the percentage differences in average emissions and fuel consumption. The statistical significance of these differences was tested through the Welch's t-test, or unequal variances t-test, at the 95% confidence level. Statistical tests on the results of RDE tests were not performed because real-world conditions are not strictly repeatable as they are strongly affected by intrinsically variable traffic intensity, driver's behaviour, and environmental conditions.

The intended application of the LCA was to compare the environmental impacts of using a C-segment GDI Euro 6d-TEMP passenger car fuelled by four blends of petrol (Fuel A, B, C, and D). The impact of the ICEV was also compared with the use of a C-segment BEV. The LCA was performed following the ISO standards (ISO, 2020, 2006) and the International Reference Life Cycle Data System guidelines (European Commission et al., 2010). The functional unit was defined as "driving 1 km in Europe with a C-segment car that fulfils the Euro 6d-TEMP standard". The lifetime mileage chosen for the ICEV was 210,000 km (Weymar and Finkbeiner, 2016), and it was assumed that the BEV had the same lifetime (Essen et al., 2017). The life cycle model was attributional, i.e., depicting the existing supply-chain processes. A "cradle-to-grave" system boundary was adopted, consisting of production, use and end-of-life of the cars, including capital goods (road, infrastructure, and equipment). Cases of multifunctionality (i.e., when the process delivers more than one good and/or service) were solved accordingly to the ISO hierarchy (ISO, 2020). Different feedstocks were assessed for bio-ETBE, bioethanol, and methanol production (Table 2).

For biofuels, the assumption of carbon neutrality was adopted. For e-methanol production, the CO_2 was assumed to be captured from the flue gas of a cement plant. Since CO_2 is captured instead of being released into the atmosphere, the CO_2 released from the combustion of e-methanol was considered neutral like biogenic CO_2. Emissions from fuel, lubricant, tires, brakes, and road surface were included. The production, maintenance, and end-of-life of the ICEV were modelled according to the tested car, while for the BEV they were modelled referring to a hypothetical average C-segment passenger car in Europe. All the data sources for the life cycle inventory were retrieved from the literature and were described in Puricelli et al. (2021). WLTC emission factors were used in the present LCA as default values for the exhaust emissions (CO, NMHC, NOx, PM, CH_4, CO_2, NH_3, N_2O, methanol) and fuel consumption of the ICEV. For the life cycle impact assessment phase, the EF method 3.0 (Fazio et al., 2018; Saouter et al., 2020) was used, considering all mid-point impact categories.

Table 2. Energy carriers examined in the LCA.

Energy carrier	Vehicle	Fuel	Production process	Feedstock
Petrol	ICEV	A, B, C, D	Crude oil refining	Crude oil
ETBE	ICEV	A	Etherification	Ethanol from ethylene and isobutylene
Bio-ETBE	ICEV	A, C	Etherification	Bioethanol from sugar beet or wheat straw and isobutylene
Bionaphtha	ICEV	B	Hydroprocessing	80% palm oil and 20% used cooking oil
Bioethanol	ICEV	B, D	Fermentation	Sugar beet or wheat straw
Methanol	ICEV	D	Steam methane reforming and methanol synthesis	Natural gas
Biomethanol	ICEV	D	Steam methane reforming and methanol synthesis	Biomethane from sewage sludge or manure or municipal organic waste
	ICEV	D	Biomass gasification and methanol synthesis	Willow chips
E-methanol	ICEV	D	CO_2 hydrogenation	CO_2 from cement plant and H_2 from wind electricity
Electricity	BEV	-	Various (according to the European production mix)	

3. Results and discussion

3.1. Literature review on biofuels

The scientific literature review (Puricelli et al., 2021) showed that the most relevant biofuels in Europe are biodiesel, hydrotreated vegetable oil (HVO), bioethanol, and biomethane. In 2019, the biofuels most consumed in transport in the EU28 were biodiesel and HVO (totalling 80.5% energetic share of biofuels), followed by bioethanol (18%) and biomethane (1.5%) (EurObserv'ER, 2020). After a stagnation from 2012 to 2016, the consumption of biofuels in Europe increased during 2017 and 2018 to 4.5% of the energy share in road transport and non-road mobile machinery. France, Germany, Spain, the United Kingdom, and Italy accounted for about 70% of the EU consumption of biofuels in 2018.

The 86 reviewed LCA studies showed that the WTW climate change impact of biofuels is generally lower than that of diesel fuel and petrol, with average GHG emission savings depending on the type of biofuel: 70% for biohydrogen, 63% for biomethane, 41% for pure biodiesel, between 54% and 7% for bioethanol (depending on its blend percentage, between 100% and 10%). The advantages of biofuels for climate change are questioned by the uncertainty surrounding the land-use change (LUC), but impacts on LUC are rarely considered in the LCA studies. Substantial amounts of CO_2 stored in trees and soil can be released due to the change from one land use into energy crops. LUC can also be indirect when biofuel production pushes the displaced agricultural production into non-cropland. Moreover, biofuels use often leads to higher impacts on non-GHG-related environmental impact categories when compared to fossil fuels use.

3.2. Laboratory and on-road tests

All the exhaust emissions of the tested fuels were compliant with Euro 6 standard (for WLTC) and with Not-To-Exceed limits (for RDE). Therefore, none of the fuels showed any regulatory issue for CO, HC, NMHC, NOx, PM, and PN. The relative variations between the three experimental blends and Fuel A, based on the results of the WLTC tests, are summarised in Table 3; only the statistically significant variations are reported.

Table 3. Statistically significant changes according to reference Fuel A. Legend: n.s. = not significant, WLTC = Worldwide harmonized Light vehicles Test Cycle.

Parameter	WLTC phase	Unit of measurement	Fuel A	Fuel B	Fuel C	Fuel D	Euro 6 limit (GDI)
CO	Total trip	mg/km	193.46	n.s.	150.32 (-22.3%)	n.s.	1000
NO_x	Total trip	mg/km	5.27	n.s.	7.94 (+50.7%)	7.80 (+48.1%)	60
CO_2	Total trip	g/km	153.51	142.98 (-6.9%)	n.s.	n.s.	-
Fuel consumption	Total trip	MJ/km	2.12	1.99 (-6.4%)	2.10 (-1.0%)	n.s.	-
NO_2	Total trip	mg/km	3.85	n.s.	3.74 (-2.9%)	n.s.	-
Methanol	Total trip	mg/km	0.03	n.s.	n.s.	0.13 (+294.8%)	-
Formaldehyde	Low phase	mg/km	0.82	n.s.	n.s.	1.27 (+55.5%)	-
Acetaldehyde	Low phase	mg/km	0.57	0.90 (+59.1%)	1.09 (+92.3%)	1.07 (+89.3%)	-
Aldehydes	Low phase	mg/km	1.54	n.s.	2.20 (+43.0%)	2.48 (+61.4%)	-

Compared with WLTC tests, the RDE tests resulted in higher fuel consumption and emissions of NOx and CO_2. This result was expected because, compared with the WLTC, driving on the road involves heavier engine loads, decelerations and accelerations. Moreover, the load during RDE tests was higher due to the measuring equipment in the car's boot and two people on board instead of one. Conversely, CO, HC, CH_4, and PN (particle number) average emission factors were lower for the RDE tests than those obtained in the WLTC tests. These results are explained by the greater mileage of an RDE test (compared with that of the WLTC), which leads to a lower contribution of cold-start emissions to the overall emission factors.

3.3. Life Cycle Assessment

The ICEV powered by Fuel A with ethylene-based ETBE (the fossil reference fuel of this study) had the highest impact on climate change (emission of 243.8 g CO_2 eq/km), only slightly reduced with the substitution of ETBE with bio-ETBE (241.7-241.8 g CO_2 eq/km, depending on the feedstock). Fuel B was the most promising blend (219.0-219.5 g CO_2 eq/km). Fuel C and D caused similar impacts, ranging from 234.9 to 235.6 g CO_2 eq/km for Fuel C and from 235.1 g CO_2 eq/km (with sludge-based biomethanol) to 240.9 g CO_2 eq/km (with natural gas-based methanol) for fuel D. The GHG emission savings of the experimental fuels, compared with Fuel A with fossil ETBE, ranged from 0.8% to 10.1%. Even though its production impacted 45% more than the ICEV, the BEV had the lowest impact (144.3 g CO_2 eq/km) because exhaust emissions are absent. As shown in Figure 1, the CO_2 eq. break-even points stayed inside the 30,000-45,000 km window. For Fuel D, only the means of the cases with the same type of bioethanol were included because the results were insensitive to the methanol type.

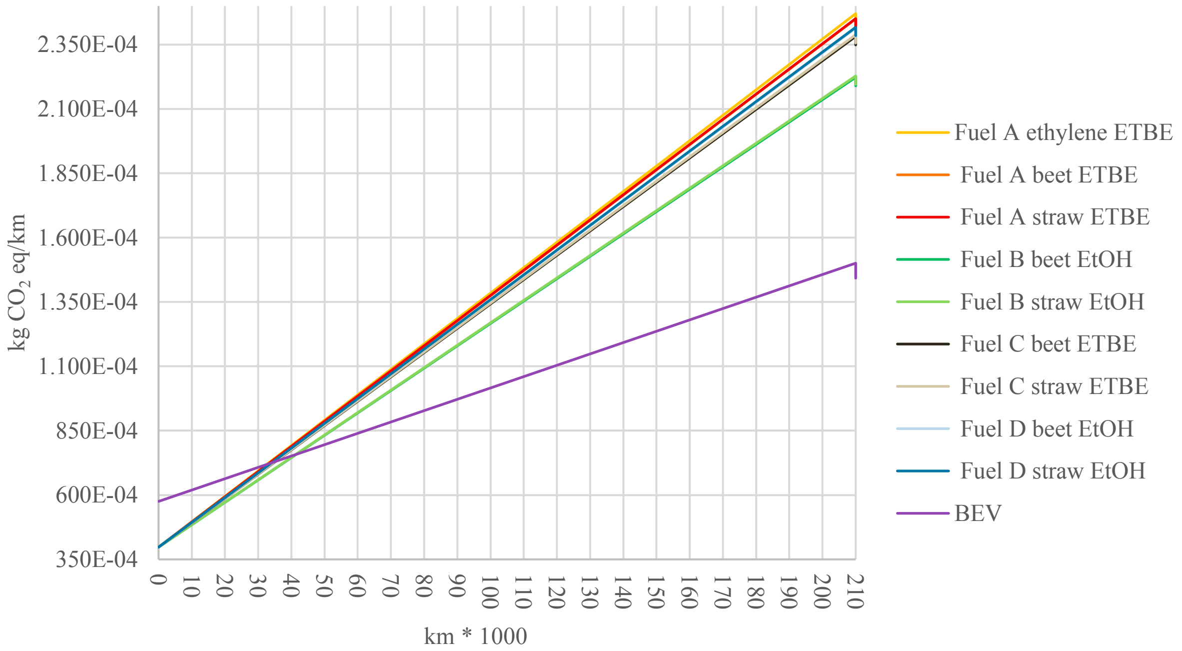

Fig. 1. Impact on climate change of the ICEV and the BEV along with their mileage, excluding land-use change. Legend: BEV = battery electric vehicle, ETBE = ethyl tert-butyl ether, EtOH = ethanol, ICEV = internal combustion engine vehicle.

At 0 km the impact corresponds to the production of the car. Next, the impact gradually rises during the use phase of the car, which involves the production of energy carriers, exhaust and non-exhaust emissions, car maintenance, and road construction and maintenance. For both ICEV and BEV, the use phase was dominant. For the ICEV, in particular, the exhaust emissions represented more than 50% of the impact and were exclusively driven by the emissions of CO, CO_2, CH_4, and N_2O. However, biogenic CO and CO_2 emissions were not counted, and the emissions of biogenic CH_4 had a reduced impact compared to the fossil CH_4. Bionaphtha contributed to the high GHG savings of Fuel B, thanks to the high biogenic carbon content of bionaphtha (84.0% m/m) compared with those of bioethanol (52.2% m/m), biomethanol (37.5% m/m), and bio-ETBE (24.5% m/m). At the lifetime mileage of 210,000 km the overall impacts are slightly reduced thanks to the beneficial recycling of materials obtained from the treatment of end-of-life vehicles.

The results changed after including an estimation of LUC effects in the impact assessment. Fuel B was the only blend significantly affected by the LUC, due to palm oil cultivation for bionaphtha production. After counting the LUC effect, the impact of the ICEV powered by Fuel B reached 246 g CO_2 eq/km. Although the ICEV fuelled by the analysed fuel blends and the BEV potentially guaranteed a reduction of the impacts on climate change and fossil resources, the picture was less straightforward for the other 14 impact categories (Table 4).

All the fuel options increased the impacts on marine eutrophication, terrestrial eutrophication, and land use. Fuel B, C, and D reduced the impacts for ozone depletion and ionising radiation impact categories, while the BEV just reduced ozone depletion. All the experimental fuels increased impacts in freshwater ecotoxicity and particulate matter impact categories, while the BEV reduced them.

Despite the significant influence of exhaust emissions on climate change, they were almost irrelevant for the other impact categories, compared with the emissions of other life-cycle stages of the car. Firstly, combustion pollutants do not affect several impact categories, such as ozone depletion, ionising radiation, freshwater eutrophication, land use, water, and resources. Secondly, current emissions control technologies, like the three-way catalyst and gasoline particulate filter fitted to the tested ICEV, reduce the emission of different pollutants released from the tailpipe. For example, tailpipe particulate matter emissions were insignificant compared to particulate matter emissions from tyre, brake, and road surface wear and with emissions related to the production of fuels, cars, and roads. Also, for the acidification impact category, the exhaust emissions of NOx and NH_3 were irrelevant compared with those caused by the production of fuels and cars. Therefore, the increase of around 50% in NOx emissions seen in Table 3 for Fuel C and D did not affect the overall impact. The complete set of results was discussed in Puricelli (2021).

Table 4. LCA results for 16 impact categories, expressed as percentage difference compared with Fuel A containing ethylene-based ETBE. Only the means of the cases having the same type of bioethanol were included in the rows regarding Fuel D. The red and bold values refer to impact variations higher than +5%. The green, italic, and underlined values refer to impact variations lower than -5%. Impact variations between -5% and +5% were considered not substantial (black values). Legend: BEV = battery electric vehicle, ETBE = ethyl tert-butyl ether, EtOH = ethanol.

Assessed case	Impact category															
	Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals
Fuel A beet ETBE	-0.8	0.0	0.0	-0.3	**5.2**	-0.8	0.0	**10.6**	-0.9	**7.6**	**26.1**	0.4	1.7	-4.2	-0.9	0.0
Fuel A straw ETBE	-0.8	0.3	0.1	-0.1	0.5	1.1	0.5	0.5	-0.7	4.0	1.5	1.3	0.9	0.6	-0.8	0.0
Fuel B beet EtOH	*-10.1*	*-12.5*	*-8.9*	2.8	**30.9**	-3.4	0.8	**52.8**	1.5	**116.8**	**140.2**	**5.5**	**23.5**	**28.1**	*-11.1*	1.3
Fuel B straw EtOH	*-9.9*	*-11.0*	*-8.4*	3.6	**8.0**	**5.9**	3.5	4.0	2.4	**99.3**	**21.0**	**9.7**	**19.4**	**51.3**	*-10.6*	1.4
Fuel C beet ETBE	-3.6	*-5.3*	-4.6	0.1	**30.5**	-4.5	0.0	**61.8**	0.2	**48.2**	**159.4**	2.0	**9.8**	*-5.3*	*-5.1*	0.7
Fuel C straw ETBE	-3.4	-3.5	-4.1	1.2	1.7	**7.2**	3.5	0.4	1.3	**26.2**	**9.5**	**7.3**	4.6	**24.0**	-4.5	0.8
Fuel D beet EtOH	-2.3	-3.3	-1.7	0.3	**16.6**	-1.8	0.4	**33.3**	-0.9	**17.7**	**84.7**	1.1	**6.8**	-4.4	-3.4	0.3
Fuel D straw EtOH	-2.2	-2.4	-1.4	0.8	2.3	4.0	2.1	2.8	-0.3	**6.8**	**10.3**	3.7	4.2	**10.1**	-3.1	0.4
BEV	*-40.8*	*-69.6*	**131.7**	*-30.5*	*-10.9*	3.7	3.5	-1.8	**221.5**	**32.9**	**12.9**	*-61.6*	4.5	**108.5**	*-24.6*	*-57.3*

4. Conclusions

Until electric mobility becomes mainstream, biofuels can be a promising alternative to fossil fuels, provided they are produced from low-LUC-risk feedstocks. None of the tested fuels showed any criticality for tailpipe emissions based on the performed tests. The exhaust emissions of Fuel B (containing bionaphtha and bioethanol) were particularly interesting due to the reduction in CO_2 emission (-6.9% m/m). The emission factors obtained from the WLTC tests were used in an LCA of a C-segment petrol car. The LCA results indicated that all the tested fuels potentially guaranteed a slight reduction in the impact on climate change (0.8-10.1%). However, using a car designed to be fuelled by a blend containing a higher percentage of renewable fuels would probably result in a lower impact. The BEV released less cradle-to-grave GHG emissions than the fossil ICEV (-40.8%). The break-even point for the CO_2 eq emissions of the BEV and the ICEV was between 30,000 km and 45,000 km, depending on the fuels. For the remaining impact categories, the picture was less straightforward. It was found that, except for the climate change, for the other 15 impact categories, the exhaust emissions from ICEV have a very marginal role in the overall environmental impacts.

Therefore, concerning the fossil car fleet, policymakers should focus more on reducing the impact related to the production of the fuels and the vehicles. In addition, future research projects should evaluate other types of vehicles and segments of cars, 3rd and 4th generation biofuels, besides considering the effect of car's heating, air conditioning and on-road performance of BEV.

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