sustainability

MDPI

Article

Advanced Emission Controls and Sustainable Renewable Fuels for Low Pollutant and CO_2 Emissions on a Diesel Passenger Car

Joachim Demuynck [1,*], Roland Dauphin [2], Marta Yugo [2], Pablo Mendoza Villafuerte [1] and Dirk Bosteels [1]

[1] Association for Emissions Control by Catalyst, 1030 Brussels, Belgium; pablo.mendoza-villafuerte@aecc.eu (P.M.V.); dirk.bosteels@aecc.eu (D.B.)
[2] Concawe, 1160 Brussels, Belgium; roland.dauphin@concawe.eu (R.D.); marta.yugo@concawe.eu (M.Y.)
* Correspondence: joachim.demuynck@aecc.eu; Tel.: +32-27068162

Abstract: Research efforts into advanced emission control systems led to significant reduction of pollutant emissions of modern internal combustion engines. Sustainable renewable fuels are used to further reduce their Well-to-Wheels greenhouse gas emissions. The novel aspect of this paper is the compatibility investigation of existing advanced emission control technologies for achieving low pollutant emissions with the use of sustainable renewable fuels with vehicle tests. This is done on a diesel demonstrator vehicle, equipped with Lean NOx trap and dual-SCR technologies in combination with a 48V mild-hybrid powertrain. Tailpipe pollutant and CO_2 emissions are measured for market diesel fuel with 7% renewable fatty-acid-methyl-ester (FAME) (B7), diesel fuel with 30% FAME (B30), and 100% renewable hydrotreated vegetable oil (HVO). Results show no significant difference in pollutant emissions between the different fuels used. In a second part of the study, a Well-to-Wheels (WTW) analysis is conducted. This includes different pathways for the biomass-to-liquid fuels that were tested on the vehicle, as well as a power-to-diesel (e-diesel) assessment. Results show that significant WTW CO_2 reductions are possibly compared to the state-of-the-art market diesel fuel. Part of this reduction is already possible for the existing fleet as most of paraffinic compounds are drop-in for market diesel fuel.

Keywords: emission control; sustainable fuel; passenger car; diesel; HVO; B30

Citation: Demuynck, J.; Dauphin, R.; Yugo, M.; Mendoza Villafuerte, P.; Bosteels, D. Advanced Emission Controls and Sustainable Renewable Fuels for Low Pollutant and CO_2 Emissions on a Diesel Passenger Car. *Sustainability* **2021**, *13*, 12711. https://doi.org/10.3390/su132212711

Academic Editor: Jelica Pavlovic

Received: 30 September 2021
Accepted: 5 November 2021
Published: 17 November 2021

1. Introduction

To improve the air quality and reduce the health impacts in EU, successive European emission standards have been introduced to reduce pollutant emissions from road transport. For passenger cars, the most recent addition has been the introduction of the Real Driving Emissions (RDE) procedure within Euro 6. With RDE, the EU became the first region in the world to introduce real world on-road testing to address the gap between on-road emissions and laboratory test results. As part of RDE, a new car is tested on public roads and over a range of different conditions. This includes low and high altitudes and speeds and uphill and downhill driving, as well as a variety of vehicle payloads and ambient temperatures.

These successive emission standards promoted innovation in catalyst and filter technology design as well as emissions control system layout within an integrated approach of powertrain development, in addition to progress in engine and combustion technology [1–7]. Examples of state-of-the-art systems for the latest Euro 6d passenger car standards include close-coupled catalysts for cold-start and low speed and load driving in the city, and underfloor catalysts for high speed and load area on the motorway for both diesel and gasoline passenger cars. Total catalysts and filter volumes are designed to cope with peak engine pollutant flow. In the specific case of diesel passenger cars, some of the technology innovations include:

- Oxidation catalysts, remaining a key technology for diesel engines and converting carbon monoxide (CO) and hydrocarbons (HC) into CO_2 and water.

- Diesel particulate filters (DPFs), removing up to 99.9% of particles coming from the engine, including ultrafine particles. Reference emissions factors from HBEFA [8] for Euro 6 diesel vehicles are well below the limit of 6×10^{11} #/km. These emissions factors include the contribution of the DPF regeneration. Since the Euro 5b exhaust emissions legislation was introduced in 2011, DPFs are effectively mandatory.
- A combination of different deNOx exhaust aftertreatment systems [9,10], being used to reduce and control tailpipe NOx emissions of diesel cars, including selective catalytic reduction (SCR) and NOx traps. In the SCR system, urea is dosed to obtain ammonia as a reagent to convert NO and NO_2 into nitrogen over a special catalyst system [11]. A growing number of diesel cars registered after September 2015 (predominantly Euro 6-compliant vehicles) are equipped with this technology.

On-road NOx and PN emissions have been reduced significantly as a consequence and this is confirmed by OEM data at Type Approval [12,13] and independent third-party testing [1–15]. Further evolution is expected toward Euro 7 for which the legislative development process is ongoing. It continues to consider modifications to limits and test procedures to ensure lowest possible vehicle pollutant emissions.

Next to pollutant emissions, GHG emissions from road transport are a major concern due to their contribution to climate change. In the last two decades, regulations in the EU have encouraged the development and incorporation of renewable fuels for transport with a view to reduce its carbon footprint. In a first version published in 2009, the renewable energy directive [16] required transport to meet a minimum 10% target of renewables on an energy basis. Addressing the requirements of the regulation, the stakeholders of the fuel industry have developed different types of renewable fuels, mostly derived from food and feed crops as well as wastes. If properly selected in terms of feedstock and processes, these renewable fuels already deliver GHG reductions in the transport sector on a Well-to-Wheels (WTW) basis [17]. In 2018, the recast of the renewable energy directive [18] made the requirements more stringent toward a 2030 target: more renewables used in transport (14% on an energy basis) and a specific minimum requirement on the development of advanced biofuels, set at 3.5%. The latter requires the fuel industry to develop new conversion processes such as biomass-to-liquids (BTL), among others, being able to process non-food/crop-based feedstocks, such as lignocellulosic materials from agricultural or forestry residues. These advanced biofuel pathways can deliver further WTW GHG reductions [17]. Very recently, the European Commission published its proposal for the "Fit for 55 package" [19], aiming at reducing the EU's GHG emissions by 55% compared to a 1990 reference. This package includes a proposed recast of the renewable energy directive RED II(I) [20], with a target of renewables incorporated in the transport pool until reaching a minimum of 13% reduction in their carbon intensity and therefore, expressed in GHG terms instead of in energy ones this time. The proposal also opens the door to a new type of renewable fuels from non-biological origin (RFNBO) and low-carbon fuels called recycled-carbon fuels (RCF). RFNBO and RCF could be composed of power-to-liquids (PTL) fuels, also called e-fuels, as they are derived from CO_2 and renewable electricity. These e-fuels can also deliver GHG reduction on a WTW basis, providing that CO_2 is considered as a waste and/or directly extracted from the atmosphere [17].

In its "Fit for 55 package" the European Commission also published a proposal for setting new CO_2 standards for passenger cars and vans [21]. In the current version of the proposal, a reduction of 55% (resp. 50%) of CO_2 emissions by 2030 is foreseen in WLTP terms compared to a 2021 reference for passenger cars (resp. for vans), followed by a reduction of 100% by 2035 for both cars and vans. This is based on tailpipe emissions only (Tank-to-Wheels emissions, TTW) and does not consider upstream emissions (Well-to-Tank, WTT), whether they are positive or negative, nor life cycle assessment. The overall GHG emissions are what matters regarding climate change, and not only those measured at the tailpipe. Therefore, this work intends to contribute to the scientific discussion by providing an estimate of the Well-to-Wheels GHG emission reduction when the selection of different fuel production pathways (WTT) and their related properties are combined with the results of real experimental tests. For this purpose, WTT data from the JEC WTT v5 report were used [17], following a marginal approach and widely used as a source in different European Commission publications (e.g. [22,23]). The authors acknowledge that there is no single WTT value for each type of fuel (as clearly stated in the JEC WTT v5 report) and as such, different ranges can be found in the literature depending on factors such as different methodological approaches followed (e.g., marginal vs average allocation methods) or feedstocks used [24–26]. In this context, the selected fuel pathways routes are to be considered as representative examples of the European context.

The work presented here entailed first an experimental part with tailpipe pollutant and CO_2 emissions measurements on a demonstrator vehicle. In the second part, a WTW analysis was conducted to assess the sensitivities regarding production pathways. The originality of this work is that, for obtaining the WTW assessments, it combined the WTT data collected from the JEC v5 report with their related experimentally measured emissions at the tailpipe (TTW), these two values being connected through the fuel properties measured in a laboratory. Three diesel-like fuels were selected: a market grade diesel with a 7 %*v/v* (B7) of fatty acid methyl ester (FAME) as reference, a diesel fuel with a higher FAME blend up to 30 %*v/v* (B30), and a drop-in diesel using a hydrotreated vegetable oil (HVO) as a representative example of paraffinic fuels.

- The FAME content in the B30 can be derived from several different crops or from waste cooking oil, which allows interesting sensitivities around their Well-to-Wheels GHG emissions. Currently, the blending wall limits the use of FAME in conventional diesel engines up to 7 %*v/v*. Beyond GHG-related aspects, as FAME is known to emit more engine-out NOx due to their oxygen content [27,28], the study wants to assess whether this effect is still present at the tailpipe after going through a high-performance deNOx emission control system.
- The hydrotreated vegetable oil (HVO) is solely made of paraffinic compounds. An extensive test plan allowed to evaluate the impact of HVO on the tailpipe emissions of the vehicle. Although HVO's carbon chain length may be different from those of other paraffinic fuels such as BTL or e-diesel, the similarity in the paraffinic nature of all these fuels led the authors to assimilate HVO to a representative of the whole paraffinic fuels family, allowing sensitivity calculations regarding their production pathways (WTT), assuming similar fuel properties and tailpipe impacts (TTW).

2. Materials and Methods

2.1. Demonstrator Diesel Vehicle

The base diesel vehicle (Figure 1) for the demonstrator project is a C-segment car equipped with a Euro 6b diesel engine. The vehicle has a 6-speed manual gearbox in combination with front wheel drive. Key features of the downsized, 4-cylinder, 2-valve diesel engine include a displacement of 1.5 L, 1600 bar common rail fuel injection system, 1-stage variable geometry turbo charger with e-actuator and air/air intercooler. It also features a 48V mild-hybrid system. The mild-hybrid electric motor can support the internal combustion engine up to 10 kW. During acceleration phases, hybrid-assist provides torque in order to support the diesel engine and reduce fuel consumption and CO_2 emissions. Additional CO_2 reduction is obtained by stop-start functionality when the car does not move. During deceleration and braking phases, the electric generator recovers the kinetic energy in order to recharge the battery. During take-off or acceleration at low engine revolutions, hybrid-assist will also provide additional torque to improve reactivity and avoid gear downshifting. NOx engine-out emissions are controlled by a combination of uncooled high- and cooled low-pressure exhaust gas recirculation (EGR) systems.

Figure 1. Demonstrator diesel vehicle.

2.2. Emissions Control System

The original emissions control system was removed and replaced by a lean NOx trap (LNT) and dual selective catalytic reduction (SCR) system, shown in Figure 2.

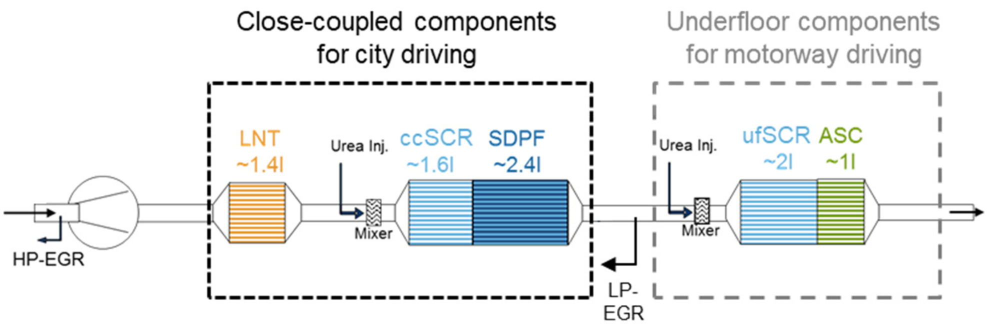

Figure 2. The emissions control system consists out of a lean NOx trap (LNT) and dual selective catalytic reduction (SCR).

The LNT and close-coupled SCR mainly reduce the NOx emissions during city driving at low exhaust temperatures. For NOx-control under motorway driving conditions, a second SCR catalyst and an ammonia slip catalyst (ASC) are added to an underfloor position with a 2nd urea dosing unit. The combination of different components positioned along the exhaust line broadens system deNOx performance across a wide variety of driving conditions. The LNT also fulfills the role of a diesel oxidation catalyst (DOC), reducing CO and HC emissions. The close-couple SCR is partly integrated on the DPF which reduces the particulate emissions. This system contains technologies which are all available on the market, and the implemented layout is similar to state-of-the-art Euro 6d layouts [29]. All catalyst components used in this work were tested following a hydro-thermal oven ageing procedure representative of the vehicle lifetime. In addition, around 15,000 km was accumulated during the project before the final emissions tests were conducted. Further details of the system are described in [30,31], including thermal management and functionalities of the 48V mild-hybrid system to support emissions control: the electric motor acts as a generator to increase the engine load after cold-start, the electric motor compensates for torque fluctuations during LNT regeneration and the electric motor covers part of the transient accelerations.

2.3. Emissions Tests

A variety of emissions tests was conducted to characterize the emissions performance. In addition to regulatory emissions tests (WLTC and RDE), different tests were conducted on the road and in the lab to cover urban (Berlin and Transport for London interpeak cycle), uphill (driving in the Harz area of Germany, up to 700 m), and motorway driving around Berlin (vehicle speeds up to 160 km/h). The engine load points, vehicle speed traces, and exhaust temperature histograms of some of these tests are shown in Figure 3. The TfL test consists mainly of low-load driving, often below the 200 °C exhaust temperature line. The combination of short distance (9 km) and low average vehicle speed (13.9 km/h including idle) makes it a very challenging cold-start test. The exhaust temperature histogram shifts to higher temperatures when going to the WLTC, RDE and motorway test. An RDE test was also done on the chassis dyno, using the trace from an on-road measurement. All these tests were conducted on market B7 diesel. A subset of the tests was conducted to validate the emissions performance on B30 and HVO. All tests include an initial cold-start after soaking the vehicle at ambient temperature the night before.

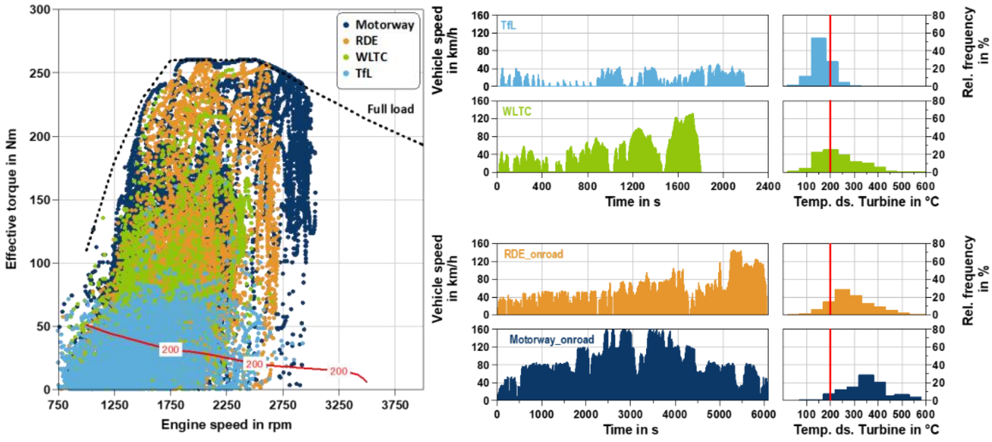

Figure 3. Driving conditions covered (engine load, vehicle speed, and exhaust temperature).

During tests on the chassis dyno, gaseous tailpipe emissions have been measured with an AVL AMA i60, sampling at the tailpipe, for THC, NOx, CO, and CO_2. PN emissions were measured with an AVL particle counter, sampling from the dilution tunnel. On-road emissions are measured with an AIP PEMS for NOx, CO, and CO_2. A PEMS-PN was only available for a limited number of tests. Both dyno and PEMS analyzers fulfil the legal requirements for measurement accuracy. In addition, ECU type NOx sensors have been used during both on-road and on-dyno tests.

2.4. Fuels

A set of three fuels was selected for the test campaign, including market fuels and fuels already used in niche markets without any engine or vehicle modifications. The rationale for selecting such fuels was to evaluate the effects that they could have on pollutant emissions while bringing renewability benefits (GHG) to existing and new vehicles. The three fuels are described in the following paragraphs and their key properties, including the laboratory measurement method, are listed in Table 1.

Table 1. Key properties of test fuels.

	Units	Method	B7	B30	HVO
Density	kg/L	EN ISO 12185	0.838	0.825	0.780
Cetane number	-	EN ISO 5165	52.0	54.0	>70
Viscosity at 40 °C	mm^2/s	EN ISO 3104	2.802	2.118	2.863
FAME content	$\%v/v$	EN 14078	6.4	29.9	<0.1
PAH content	%m/m	IP 391 mod	3.5	0..3	<0.01
Total aromatics	%m/m	IP 391 mod	25.8	4.1	0.2
Carbon content	%m/m	ASTM D3343 mod	85.94	83.62	85.32
Hydrogen content	%m/m	ASTM D3343 mod	13.35	13.16	14.68

Table 1. *Cont.*

	Units	**Method**	**B7**	**B30**	**HVO**
Oxygen content	%m/m	EN 14078	0.7	3.23	<0.01
Net heating value (m)	MJ/kg	ASTM D3338	42.74	41.73	43.62
Net heating value (v)	MJ/l	Calc.	35.82	34.43	34.02
CO2 intensity, TTW (calc)	gCO_2/MJ	Calc.	73.7	73.5	71.7
IBP	°C	EN ISO 3405	174.9	168.4	193.0
T50	°C	EN ISO 3405	277.0	231.5	N/A
T95	°C	EN ISO 3405	354.3	348.4	N/A
FBP	°C	EN ISO 3405	360.0	355.6	304.4

2.4.1. B7

The B7 is a market diesel fuel, representative of a current European diesel road fuel, complying with EN590. It is a mixture of fossil-based components (94%*v/v*) and FAME (biodiesel, 6%*v/v*), compliant with EN14214. Its cetane number is close to the EN590 minimum at 52 while its density is close to the EN590 maximum at 0.838 kg/L.

This fuel provides a reference for evaluating the effects of the two other fuels. Only this fuel was used for developing and calibrating the vehicle demonstrator, meaning that the two other fuels were used as "drop-in" fuels, with no further adaptations to the vehicle's settings or hardware.

2.4.2. B30

The B30 fuel is a mixture of low-density fossil-based diesel fuel (70%v/v) and FAME derived from used cooking oil (UCOME, 30%v/v). This fuel was selected to evaluate the impact of high FAME content levels, so far only used in Europe in captive fleets, on emissions. In particular, the purpose was to check whether the increased NO_x emissions historically associated with the use of high FAME fuels due to their higher oxygen content could be mitigated by the sophisticated exhaust aftertreatment system used in this study.

2.4.3. Hydrotreated Vegetable Oil (HVO)

The HVO is a paraffinic fuel derived from biological sources, compliant with EN15940. It was selected to evaluate the effects on emissions of a low density, low aromatics, high H/C ratio, and high cetane number fuel.

Due to its paraffinic nature, HVO is close in its composition to other paraffinic fuels such as those derived from biomass (BTL) or from renewable electricity and CO_2 (e-diesel). This proximity in the composition is assumed to transpose into similar combustion behavior, at least regarding Tank-to-Wheels CO_2 emissions and energy content. This similarity allowed to extrapolate the WTW CO_2 calculations of HVO to other production pathways of paraffinic fuels such as BTL and e-diesel (see Section 2.3 for further details).

2.5. Well-to-Wheel Calculation Method

The method used for calculating well-to-wheel CO_2 emissions derives from the one used in the JEC WTW report v5 [17], using the inputs from this report (well-to-tank data) and from the data from the chassis dyno experiments (tank-to-wheel data). The following equations were used to make the calculations:

$$CO_{2WTW}\left[\frac{g}{km}\right] = CO_{2WTT}\left[\frac{g}{km}\right] + CO_{2TTW}\left[\frac{g}{km}\right] \quad (1)$$

where $CO_{2WTT}\left[\frac{g}{km}\right]$ is the CO_2 emissions in g/km from well-to-tank, calculated following the method explained below, and $CO_{2TTW}\left[\frac{g}{km}\right]$ is the CO_2 emissions in g/km from tank-to-wheel, obtained via the experimental results given by the chassis dyno tests, respectively on B7, HVO, and B30. Then,

$$CO_{2WTT}\left[\frac{g}{km}\right] = CO_{2WTT,fuel\ production}\left[\frac{g}{km}\right] - CO_{2biocredits}\left[\frac{g}{km}\right] \quad (2)$$

Which can also be detailed as follows:

$$CO_{2WTT}[\frac{g}{km}] = \frac{Q_{fuel}\left[\frac{MJ}{100km}\right]}{100} \times (\sum_{all\ compounds,\ i} CO_{2intensity,\ WTT,\ i}[\frac{gCO_2}{MJ}] \times NRJ_i - \sum_{renewable\ compounds,\ j} CO_{2intensity,\ TTW}[\frac{gCO_2}{MJ}] \times NRJ_j) \quad (3)$$

where $Q_{fuel}\left[\frac{MJ}{100km}\right]$ is the fuel energy in MJ used by the vehicle for 100 km driven on the chassis dyno, as measured experimentally, $CO_{2intensity,\ WTT,\ i}\left[\frac{gCO_2}{MJ}\right]$ is the Well-to-Tank CO_2 emission factors expressed in gCO_2/MJ for the compound *i* blended in the fuel, obtained as described in Table 2, NRJ_i is the share of energy of the compound *i* blended in the fuel, $CO_{2intensity,\ TTW}\left[\frac{gCO_2}{MJ}\right]$ is the tank-to-wheel CO_2 emission factors, as described in Table 1, expressed in gCO_2/MJ. NRJ_j is the share of energy of the renewable compound *j* (i.e., not from fossil source) blended in the fuel.

Table 2. Well-to-Tank CO_2 emission factors (data extracted from JEC WTW report v5 as representative fuel production pathways).

	Feedstock	WTT Process	Pathway (WTT)	$CO_{2\ intensity,\ WTT,\ i}\ [\frac{gCO_{2eq}}{MJ\ fuel}]$
HVO	Palm oil	HPO process (NExBTL), CH4 recovery (heat credits)	POYH1b	31
	Waste cooking oil	HWO process (NExBTL)	WOHY1a	11.1
	EU mix	EU mix based on market share per feedstock (see Table 3)	HVO EU Mix	30.0
e-fuel (PTL)	Renewable electricity	Synthetic diesel: H2 produced trough water electrolysis (SOEC technology assumed) using renewable electricity, followed by Fischer-Tropsch (FT) conversion process. CO2 from industrial flue gases (waste)	RESD2a	0.81
BTL	Wood residue	Synthetic diesel from wood residue via hydrothermal liquefaction HTL (transported 500 km)	WWSD2	27.49
	Wood residue	Synthetic diesel from gasification of wood residues (500 km distance) and FT conversion coupled with carbon capture and storage	WWSD1aC	−100.54
FAME	Rapeseed oil	Rape (RME) feedstock to FAME with meal exported as animal feed (AF)and glycerine exported to chemicals.	ROFA1	48.44
	Palm oil	FAME from palm (POME), meal to AF with no CH4 recuperation, heat credits and glycerine to biogas	POFA3b	31.82
	Waste cooking oil	FAME from waste cooking oil	WOFA3a	8.33
Fossil diesel	Crude oil	EU mix − JEC/Concawe marginal approach	COD1	18.9

The analysis of Table 2 already gives interesting insights on the renewability benefits in terms of GHG emissions of the different fuel production pathways studied in this work. Fuels produced from waste cooking oil, whether they become HVO or FAME, present low Well-to-Tank emissions. This is because wastes are considered not to require any emissions to produce them (the production emissions are allocated to the first user); therefore, the emissions count only starts from the waste collection process, avoiding the emissions related to the production of the feedstock itself. Then, fuels made from food-and-feed crops (so-called "first generation" biofuels) follow with higher emissions, in particular because of the emissions related to the feedstock cultivation steps. Still, even with the highest Well-to-Tank emission case (48 gCO_2/MJ, ROFA1 pathway), these fuels present GHG renewability benefits because they benefit from CO_2 biocredits in the range of 71.7–73.5 gCO_2/MJ. These biocredits reflect the fact that the carbon contained in these fuels was originally "captured" from the atmosphere's CO_2 (e.g., when the crop grows) and released again during the combustion, having a net-zero CO_2 impact overall, as part of the circular economy.

More interesting are advanced biofuels, biomass-to-liquids made from wood residue in this instance. The data show that syndiesel produced from wood residue via hydrothermal liquefaction can limit Well-to-Tank emissions to quite low values. Even if the HTL process can be quite complex and energy (and therefore emission) intensive, higher than conventional fossil fuels, this is partly compensated by the very low emissions generated by the feedstock collection and bailing. Moreover, using a combination of a gasification and Fischer-Tropsch process with carbon capture and storage schemes, the overall Well-to-Tank GHG emissions can even become negative. These negative emissions are enabled by the fact that, after the gasification process, part of the carbon captured in the biomass (hence, considered as bio-CO_2 as it was originally taken from the atmosphere) is directly captured and permanently buried underground generating net negative GHG emissions in what it is called bioenergy CCS schemes (BECCS). The generation of negative emissions pathways by different natural sinks or BECCS schemes are deemed to be essential enablers of the net-zero GHG economy in the future because they provide a compensation for the remaining emissions of the hard-to-abate sectors.

Power-to-liquid, also called e-fuels, represent an interesting alternative despite their pretty energy intensive production pathways, having close to zero Well-to-Tank emissions when fully produced from renewable electricity. The pathway presented in Table 2, using CO_2 from industrial flue gases, corresponds to the terminology "recycled carbon fuel" (RCF) in the proposed recast of the renewable energy directive [20]. This pathway can be criticized for not being truly carbon-neutral, as the fossil-based CO_2 captured from the flue gas is finally released into the atmosphere when the e-fuel burns, where it will finally accumulate. For this reason, the CO_2 credit can only be allocated once, either to the flue gas emitter who captures CO_2, or to the e-fuel producer who uses it (or any intermediate allocation split between those two), but it cannot be double-counted. In this work, it is assumed that the CO_2 credit is allocated to the e-fuel producer, providing them close to zero well-to-wheel emissions.

Finally, the Well-to-Tank emissions of fossil diesel fuel may appear quite low at this stage. As a matter of fact, crude oil already has a high energy density, and requires relatively limited efforts to extract and process it into fuels, which translates into a low energy-intensive process with limited GHG emissions. However, one must keep in mind that fossil diesel fuel does not benefit from any CO_2 biocredit, because in this instance, carbon is extracted from the underground and emitted in the atmosphere, where it accumulates.

Table 3. Share of total EU biodiesel and HVO consumption in 2017 (data extracted from JEC WTW report v5).

Feedstock	Share in FAME (%*v*/*v*)	Share in HVO (%*v*/*v*)
Rapeseed oil	52%	18%
Used cooking oil (UCO)	17%	25%
Palm oil	20%	45%
Animal fats	5%	11%
Soybean oil	5%	2%
Sunflower oil	1%	0.40%
Other oils	- *	- *

* Note: No other oils have been modelled in the JEC WTT v5. Therefore, as a simplification, UCO has been used as an approximation to describe other potential waste-based pathways.

3. Results and Discussion

3.1. Tailpipe Pollutant Emissions

The work focused on measuring NOx emissions. Data of other pollutant emissions were not available for the full range of tests. A description of data available from WLTC and RDE tests on chassis dyno will be covered for PN, PM, CO, and THC.

3.1.1. NOx

A summary of the range of NOx emissions measured for all three fuels is shown in Figure 4. Tailpipe NOx in mg/km is plotted vs. the average vehicle speed of the emission test. All data are from on-board NOx sensors for consistency because this signal is available for all on-road and chassis dyno tests. Accuracy of this data was validated compared to lab and PEMS equipment for those tests, where all equipment was mounted. A trend line is added to guide the eye for the results on market B7 diesel. It is not only the average vehicle speed that impacts the emissions, test distance is also important. Emissions in mg/km increase on the left of the graph because the dedicated urban driving tests with the lowest average vehicle speed are also the shortest, e.g., 14 km/h and 9 km for the Tfl test compared to 26 km/h and 23 km for the urban part of the RDE test. This means that the initial amount of cold-start NOx emissions in mg are averaged out over less amount of km. The emissions at the right increase, despite a constant high deNOx conversion efficiency of 95–97% because the engine-out NOx emissions of the Euro 6b engine significantly increase. This is not observed for modern Euro 6d(-TEMP) vehicles [29]. A more detailed analysis of the effects observed on market B7 diesel has been published before [30,31].

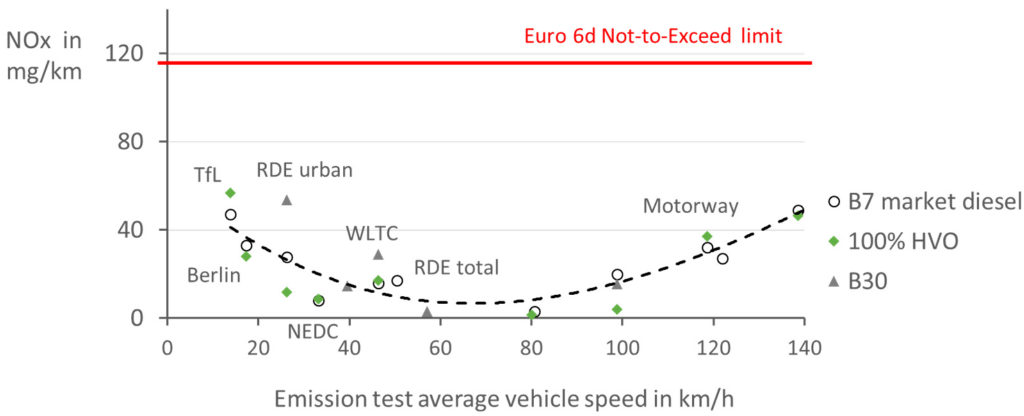

Figure 4. Tailpipe NOx emissions vs. average vehicle speed of the emission test.

On HVO, the full range of emission tests was repeated. On B30, tests included WLTC and RDE only. For HVO and B30, results follow the same trend to what was described for market B7 diesel. When using fuels with a higher cetane number, which is the case for HVO compared to B7, and to a lesser extent also for B30, the engine-out trend of NOx emissions is hardly predictable: on the one hand, a shorter auto-ignition delay leads to earlier combustions, generally leading to higher levels of pressure and temperature, hence increased NOx emissions; but on the other hand, a shorter auto-ignition delay leads to a smaller premixed flame which results in less NOx. In addition, other parameters such as the flame adiabatic temperature and the oxygen content (especially for FAME) of the compounds influence the result. Predicting the engine-out trends of NOx emissions would therefore require a thorough combustion analysis, with dedicated in-cylinder pressure sensors, which was not available on this vehicle demonstrator. Nonetheless, no matter what the engine-out trend regarding NOx emissions was, the high conversion efficiency of the aftertreatment system resulted in that no specific fuel effects were identified at the tailpipe, differences are within the expected test-to-test variability due to the impact of driver, traffic, ambient temperature, etc. [32–34]. This variability in the data for on-road testing is larger than the measurement uncertainty of the equipment. This is especially the case for the urban part including cold-start. For the B7 reference tests, variability in the urban RDE NOx result including cold-start is for example observed to be +/−20 mg/km. The B30 and HVO result in Figure 4 for RDE urban is within this range.

3.1.2. Other Pollutants

This section covers data for PM, PN, CO, and THC. For HVO, RDE tests were only conducted on the road, but without a PEMS, so there is only data for WLTC in this case. In general, no significant differences can be observed between the fuels.

Particulate emissions varied between 8.5×10^9 and 4.5×10^{10} #/km for PN (standard protocol with 23 nm cut-off) and 0.11 and 0.3 mg/km for PM on market B7 diesel over the entire duration of the project. The variation with 1 order of magnitude is caused by a combination of engine-out and DPF status effects which cannot be investigated with the available data. Figure 5 shows the result of the tests used for the comparison. Taking into account the range just mentioned, no significant differences were observed for PM on HVO and B30, with a WLTC measurement of 0.28 mg/km (HVO) and 0.32 mg/km (B30). For HVO, also PN emissions on WLTC were within the range of B7, with a measurement of 4.4×10^{10} #/km (value not available for RDE). On B30, PN measurements were higher with 1.8×10^{11} #/km on WLTC and 3.7×10^{11} #/km on RDE. This difference is not due to the fuel impact, but rather due to the order of tests, as a repeat of the RDE test on B7 after the B30 tests also resulted in 3.7×10^{11} #/km. Consequently, it must be related to an effect of the DPF status. There was however no additional data to further look into the root cause.

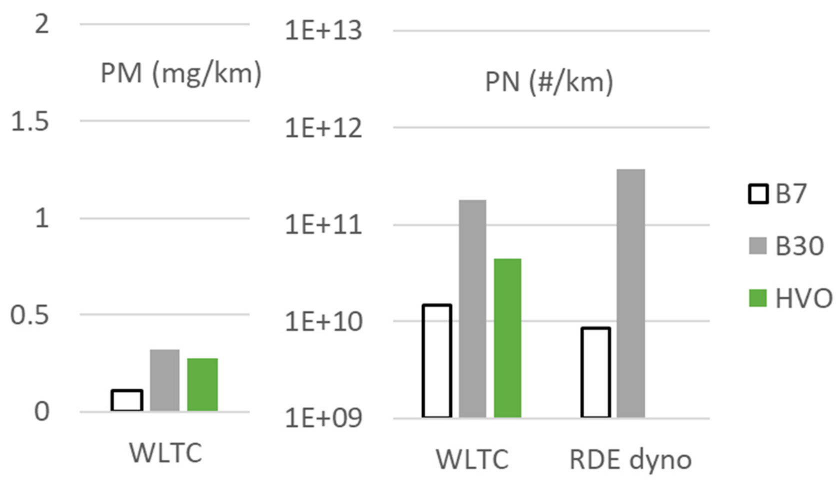

Figure 5. Particulate emissions on WLTC and RDE (dyno).

THC and CO emissions are shown in Figure 6. No significant differences can be observed. THC results on HVO (36 mg/km on WLTC) and B30 (41 mg/km on WLTC and 32 mg/km on RDE) are very similar to the range measured on B7 (32 to 40 mg/km). CO emissions measured were 38 (WLTC) and 53 mg/km (RDE) on market B7 diesel. The results on HVO (39 mg/km on WLTC) and B30 (56 mg/km on WLTC and 60 mg/km on RDE) are similar.

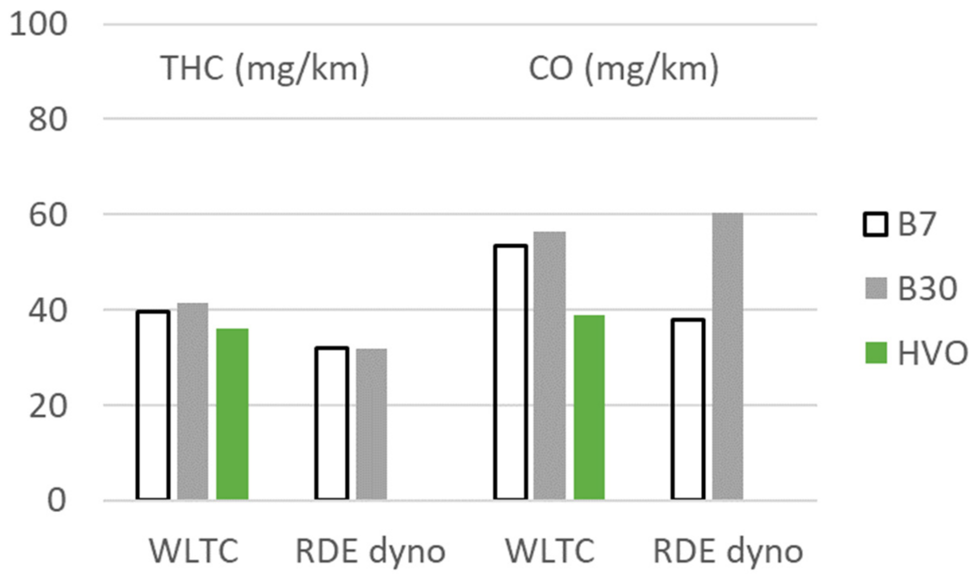

Figure 6. THC and CO emissions on WLTC and RDE (dyno).

3.2. Tailpipe CO_2 Emissions

CO_2 emissions measured at the tailpipe during the WLTC test on the chassis dyno are plotted at the left of Figure 7. Similar to the pollutant emissions, no significant differences can be observed between the B7, B30, and HVO. E-diesel has been added as well although it was not actually tested, as it is covered in the Well-to-Wheel calculation that is described in Section 3.3.

Table 4. Well-to-wheel CO_{2eq} emissions.

Tested Fuel	Feedstock	Pathway	WTW (gCO_{2eq}/km)
HVO	HVO (EU mix)	EU mix (*)	56
	HVO (Palm oil)	POYH1b	57
	HVO (Waste cooking oil)	WOHY1a	27
	BTL (HTL)	WWSD2	52
	BTL (BECCS)	WWSD1aC (*)	−147
	e-fuel (PTL)	RESD2a (*)	11
B7	FAME (Rapeseed oil)	ROFA1 (*)	146
B30			125
B7	FAME (Palm oil)	POFA3b	144
B30			118
B7	FAME (Waste cooking oil)	WOFA3a	141
B30			108

Note. (*) Selected pathway for comparison in Figure 7. Sensitivities explored around these values).

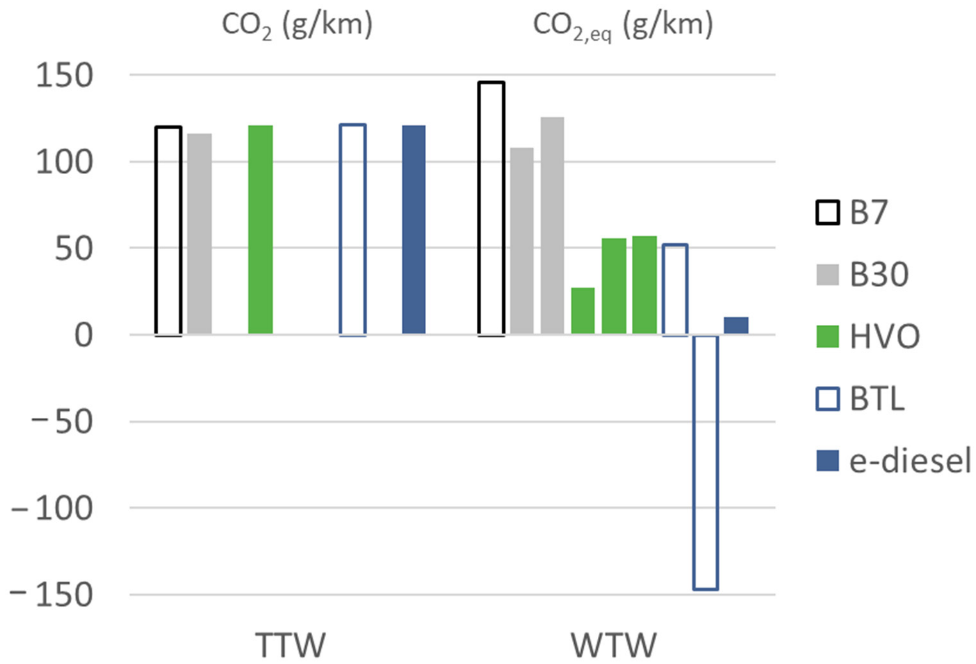

Figure 7. TTW (left) and WTW (right) CO_2 emissions for the different tested fuels. The WTW assessment looks at other greenhouse gases, so is expressed in $CO_{2,eq}$. Different bars for the same fuel type represent the range of emissions which can be obtained for a given fuel depending on its production pathway (see Table 4).

3.3. Well-to-Wheels CO_2 Emissions

WTW CO_2 emissions were calculated according to equation (1). The results are presented for each tested fuel and each fuel production pathway in Table 4 and in Figure 7, where each bar represents the average WTW value obtained for a family of production pathways, and the error bars represent the range of emission levels for the individual production pathways within the considered family. The main conclusion is that the higher the ratio of renewable compounds, the lower the WTW CO_2 emissions: very broadly speaking, B7 fuels have higher WTW emissions than B30 fuels, having themselves higher emissions than paraffinic fuels (represented by HVO as tested fuel), whatever the renewable compounds' production pathway. Indeed, a lower ratio of renewable compounds means a higher ratio of fossil diesel fuel, which does not have any biocredit (meaning fossil-based carbon being added and accumulating in the atmosphere). From this point of view, it is important that renewable compounds' properties, together with engine design, enable high blending ratios, possibly up to 100% ("drop-in" fuel), while still being compliant with the existing and future fleets. This desired "drop-in" property is generally met by paraffinic compounds which can be blended with fossil diesel fuel up to 30–50 %*v*/*v* and still comply with EN590 [35]. Alternatively, they can be used as neat compounds complying with EN15940 and be compatible with a wide range of the existing fleet, in particular with heavy-duty vehicles. This is less the case today with FAME: not that it is technically impossible—B30 (EN16709) and B100 (EN14214) being used in captive fleets [36]—but OEMs report that it requires specific vehicle maintenance and fuel handling [37], limiting the wide roll out of this solution on the roads. Notwithstanding these constraints, the European Commission proposed a revision of the fuel quality directive (FQD) where B10 would replace B7 as a standard market fuel [20].

Once the renewable compounds' ratio is given, the WTW emissions depend mainly on the conversion processes (WTT) emissions to produce them. As mentioned above, fuels derived from waste cooking oil provide the lowest WTW emissions. E-fuels also represent an interesting alternative for low WTW emissions, providing that CO_2 from flue gas is considered as a waste and that hydrogen is produced from renewable electricity. Finally, a

BTL paraffinic fuel produced via Fischer-Tropsch combined with bio-energy carbon capture and storage (BECCS) provides negative WTW CO_2 emissions which can be used to offset the remaining emissions of the hard-to-abate sectors.

4. Conclusions

This paper describes an investigation into the pollutant and CO_2 emissions of a diesel demonstrator vehicle with an advanced emission control system on different fuels. Low tailpipe pollutant emissions are measured over a wide range of driving conditions on the market diesel fuel with 7% renewable fatty-acid-methyl-ester (FAME) (B7). These results are validated on the other fuels investigated, diesel fuel with 30% FAME (B30), and 100% renewable hydrotreated vegetable oil (HVO), without any modification to vehicle hardware and software. Results show the existing technologies for achieving low pollutant emissions are compatible with the use of sustainable renewable fuels. No specific fuel effects were identified for NOx, differences are within the expected test-to-test variability due to the impact of driver, traffic, ambient temperature, etc. The data set is more limited for PM, PN, THC, and CO, but no significant differences could be identified either.

A Well-To-Wheels analysis is conducted to investigate the CO_2 emissions. This includes a power-to-diesel (e-diesel) fuel, a waste-based fuel, and biomass-to-liquids fuels. The analysis shows that significant CO_2 reductions are possible compared to the state-of-the-art market diesel fuel (from −64% to −200%). Part of this reduction is already possible for the existing fleet as most of paraffinic compounds are drop-in for market diesel fuel. This means that, under constraints of availability [38], the e-diesel, waste-based fuels, and biomass-to-liquids fuels should be rolled out in the vehicle legacy fleet and in the new fleet powered by internal combustion engines along with efficiency measures and electrification [39].

Author Contributions: Conceptualization, J.D. and R.D.; WTW analysis, M.Y.; writing—original draft preparation, J.D. and R.D.; writing—review and editing, M.Y., P.M.V. and D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would kindly like to thank members of AECC, Concawe and IPA (International Platinum Group Metals Association) for their highly valuable contributions to this study. In addition, the authors would like to thank IAV for the en-gineering work and Renault for allowing to use the vehicle hardware.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Reitz, R.D.; Ogawa, H.; Payri, R.; Fansler, T. The future of the internal combustion engine. *Int. J. Engine Res.* **2019**, *21*, 3–10. [CrossRef]
2. Nilsen, C.; Biles, D.; Mueller, C. Using Ducted Fuel Injection to Attenuate Soot Formation in a Mixing-Controlled Compression Ignition Engine. *SAE Int. J. Engines* **2019**, *12*, 309–322. [CrossRef]
3. Steinparzer, I.; Nefischer, P.; Stütz, D. The technology of the new BMW 6-Cylinder Diesel Engine for the X4 M40d. In Proceedings of the 39th International Vienna Motoren Symposium, Vienna, Austria, 26–27 April 2018.
4. Kufferath, A.; Krüger, M.; Naber, D.; Mailänder, E.; Maier, R. The Path to a Negligible NO_2 Immission Contribution from the Diesel Powertrain. In Proceedings of the Vienna Motoren Symposium, Vienna, Austria, 26–27 April 2018.
5. Wancura, H.; Wieser, W.; Krapf, M. Highly Efficient Exhaust Gas Aftertreatment for Future Diesel Applications. In Proceedings of the 10th International AVL Exhaust Gas and Particulate Emissions Forum, Ludwigsburg, Germany, 20–21 February 2018.
6. Schaub, J.; Kotter, M.; Korfer, T. 48V MHEV Diesel—Balancing Fuel Economy and Performance while Keeping Emission Advantages. In Proceedings of the Diesel Powertrains 3.0, Coventry, UK, 3–4 July 2018.

7. Severin, C.; Bunar, F.; Brauer, M.; Diezemann, M.; Schultalbers, W.; Buschmann, G.; Kratzsch, M.; Blumenröder, K. Potential of Highly Integrated Exhaust Gas Aftertreamment for Future Passenger Diesel Engines. In Proceedings of the 38th International Vienna Motoren Symposium, Vienna, Austria, 27–28 April 2017.
8. Handbook of Emissions Factors (HBEFA), Release 4.1. Available online: https://www.hbefa.net/e/index.html (accessed on 28 August 2021).
9. Umeda, H. Storage Catalyst and SCR System for RDE-Compliant Diesel Engines: A concept study on NOx storage catalyst and SCR system for RDE compliant diesel engines. In Proceedings of the 7th International MinNOx Conference, Berlin, Germany, 19–20 June 2018.
10. Seo, J.M.; Park, J.W.; Lee, J.H.; Lim, S.; Joo, K.H.; Kim, S.J.; Schaub, J.; Wittka, T.; Vovk, A.; Holderbaum, B. Fulfilment of Most Stringent EU Emission Limits by Combining NOx Storage Catalyst and SCR System in the Diesel Passenger Car. In Proceedings of the 24th Aachen Colloquium Automobile and Engine Technology, Aachen, Germany, 5–7 October 2015.
11. Börnhorst, M.; Deutschmann, O. Advances and challenges of ammonia delivery by urea-water sprays in SCR systems. *Prog. Energy Combust. Sci.* **2021**, *87*, 100949. [CrossRef]
12. ACEA RDE Monitoring Database. Available online: https://www.acea.auto/publication/access-to-euro-6-rde-data/ (accessed on 28 August 2021).
13. JAMA RDE Monitoring Database. Available online: http://www.jama-english.jp/europe/publications/rde.html (accessed on 28 August 2021).
14. Green NCAP. Available online: https://www.greenncap.com/assessments/ (accessed on 28 August 2021).
15. Emissions Analytics, EQUA Real-World Test Database. Available online: https://www.emissionsanalytics.com/equa-databases (accessed on 28 August 2021).
16. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02009L0028-20151005&from=EN (accessed on 23 July 2021).
17. Prussi, M.; Yugo, M.; De Prada, L.; Padella, M.; Edwards, R. *JEC Well-To-Wheels Report v5, EUR 30284 EN*; Publications Office of the European Union: Luxembourg, 2020; ISBN 978-92-76-20109-0. [CrossRef]
18. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02018L2001-20181221&from=EN (accessed on 23 July 2021).
19. European Green Deal: Commission Proposes Transformation of EU Economy and Society to Meet Climate Ambitions. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541 (accessed on 15 July 2021).
20. Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 as Regards the Promotion of Energy from Renewable Sources. Available online: https://ec.europa.eu/info/sites/default/files/amendment-renewable-energy-directive-2030-climate-target-with-annexes_en.pdf (accessed on 15 July 2021).
21. Proposal for a Regulation of the European Parliament and of the Council Amending Regulation (EU) 2019/631 as Regards Strengthening the CO2 Emission Performance Standards for New Passenger Cars and New Light Commercial Vehicles in Line with the Union's Increased Climate Ambition. Available online: https://ec.europa.eu/info/sites/default/files/amendment-regulation-co2-emission-standards-cars-vans-with-annexes_en.pdf (accessed on 14 July 2021).
22. European Commission. *State of the Art on Alternative Fuels Transport Systems in the European Union—2020 Update Report*; Publications Office of the European Union: Luxembourg, 2020. [CrossRef]
23. Hill, N.; Amaral, S.; Morgan-Price, S.; Nokes, T.; Bates, J.; Helms, H.; Fehrenbach, H.; Biemann, K.; Abdalla, N.; Jöhrens, J.; et al. *Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles Through LCA*; Ricardo Energy & Environment on behalf of the European Commission DG-CLIMA: Brussels, Belgium, 2020. [CrossRef]
24. Ternel, C.; Bouter, A.; Melgar, J. Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030. *Transp. Res. Part D Transp. Environ.* **2021**, *97*, 102897. [CrossRef]
25. Yugo, M.; Gordillo, V.; Shafiei, E.; Megariti, A. A look into the life cycle assessment of passenger cars running on advanced fuels. In Proceedings of the SIA Powertrains & Power Electronics Conference, Paris, France, 9–10 June 2021.
26. Wang, M.; Elgowainy, A.; Lee, U.; Bafana, A.; Benavides, P.T.; Burnham, A.; Cai, H.; Dai, Q.; Gracida-Alvarez, U.R.; Hawkins, T.R.; et al. *Summary of Expansions and Updates in GREET®2020*; Argonne National Lab. (ANL): Argonne, IL, USA, 2020.
27. Durbin, T.D.; Miller, J.W.; Johnson, K.; Hajbabaei, M.; Kado, N.Y.; Kobayashi, R.; Liu, X.; Vogel, C.F.; Matsumura, F.; Wong, P.S.; et al. CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California, Biodiesel Characterization and NOx Mitigation Study. Available online: https://ww3.arb.ca.gov/fuels/diesel/altdiesel/20111013_carb%20final%20biodiesel%20report.pdf (accessed on 23 July 2021).
28. Jeyaseelan, T.; Mehta, P.S. Correlating Engine NOx Emission with Biodiesel Composition. *J. Inst. Eng. India Ser. C* **2017**, *98*, 253–260. [CrossRef]
29. Nun, J.; Wieler, A.; Anders, C.; Betz, T. The First Mercedes-Benz Four-cylinder Diesel Engine Complying with RDE Step 2. *MTZ Worldw.* **2019**, *80*, 46–53. [CrossRef]

30. Demuynck, J.; Favre, C.; Bosteels, D.; Bunar, F.; Spitta, J.; Kuhrt, A. Diesel vehicle with ultra-low NOx emissions on the road. In Proceedings of the SAE 14th International Conference on Engines & Vehicles, Napoli, Italy, 15–19 September 2019. paper 2019-24-0145.
31. Demuynck, J.; Favre, C.; Bosteels, D.; Randlshofer, G.; Bunar, F.; Spitta, J.; Friedrichs, O.; Kuhrt, A.; Brauer, M. Integrated diesel system achieving ultra-low urban and motorway NOx emissions on the road. In Proceedings of the 40th International Vienna Motor Symposium, Vienna, Austria, 15–17 May 2019.
32. Demuynck, J.; Kufferath, A.; Kastner, O.; Brauer, M.; Fiebig, M. Improving Air quality and Climate through Modern Diesel Vehicles. *MTZ Worldw.* **2020**, *81*, 52–59. [CrossRef]
33. Williams, R.; Dauphin, R.; Andersson, J.; Ziman, P.; Rogerson, J.; Hamje, H. Fuel Effects on Regulated and Unregulated Emissions from Three Light-Duty Euro 5 and Euro 6 Diesel Passenger Cars. *SAE Int. J. Adv. Curr. Prac. Mobil.* **2021**, *3*, 428–451. [CrossRef]
34. Williams, R.; Pettinen, R.; Ziman, P.; Kar, K.; Dauphin, R. Fuel Effects on Regulated and Unregulated Emissions from Two Commercial Euro V and Euro VI Road Transport Vehicles. *Sustainability* **2021**, *13*, 7985. [CrossRef]
35. Neste Renewable Diesel Handbook. Available online: https://www.neste.com/sites/default/files/attachments/neste_renewable_diesel_handbook.pdf (accessed on 23 July 2021).
36. Biodiesel Approval for the Operation of Heavy and Light Duty Vehicles (B100). Available online: https://www.ufop.de/files/2214/1580/1039/RL_UFOP_1234_Flyer_Nutzfahrzeug_06.pdf (accessed on 23 July 2021).
37. Compatibility of Biodiesel with Petroleum Diesel Engines. Available online: https://dieselnet.com/tech/fuel_biodiesel_comp.php (accessed on 23 July 2021).
38. Panoutsou, C.; Maniatis, K. Sustainable Biomass Availability in the EU, to 2050, Imperial College Report. 2021. Available online: https://www.concawe.eu/publication/sustainable-biomass-availability-in-the-eu-to-2050 (accessed on 10 November 2021).
39. Shafiei, E.; Dauphin, R.; Yugo, M. Optimal electrification level of passenger cars in Europe in a battery-constrained future towards 2030. *Transp. Res. Part D* **2021**, in press.