Combination of advanced emission control technologies and sustainable renewable fuels on a long-haul demonstrator truck

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Abstract: Reducing CO_2 emissions from road transport is key to mitigate climate change. Heavy-duty vehicles are a hard-to-abate sector. Wider usage of sustainable renewable fuels significantly reduces Well-to-Wheel CO_2 emissions of new and existing vehicles in addition to electrification. It is also important to further reduce pollutant emissions to improve air quality, which is achieved with the application of advanced emissions control technologies.

This paper investigates compatibility of advanced emission control technologies for ultra-low pollutant emissions with two examples of sustainable renewable fuels: Hydrotreated Vegetable Oil (HVO) and e-diesel. Emissions are measured in real-world driving with a demonstrator truck and compared to reference emissions results with a market diesel.

The emissions control system of the truck integrates a close-coupled Electrically Heated Catalyst (EHC) and Diesel Oxidation Catalyst (DOC), a catalysed Diesel Particulate Filter (cDPF) and a dual Selective Catalytic Reduction (SCR) system with twin AdBlue® dosing. Both SCR catalysts contain an ammonia slip catalyst.

A reference In-Service Conformity test is run as well as an urban delivery test. Analysis of the initial cold-start phase and warm operation show ultra-low emissions are confirmed when using sustainable renewable fuels. Currently non-regulated pollutants (NH_3, N_2O and PN10) are measured in addition to standard species with a prototype Portable Emission Measurement System (PEMS).

An analysis is carried out to understand the potential Well-to-Wheel CO_2 emission reduction for the different fuels. The results of the calculation show that considerable CO_2 reductions are possible for both fuels tested. This reduction can be achieved for new and existing vehicles due to the drop-in capability of these sustainable renewable fuels.

Keywords: sustainable renewable fuel, Well-to-Wheel, ultra-low pollutant emissions

1. Introduction

The European Union has started the process to become the first climate-neutral continent by 2050. On 11 December 2019, the European Commission presented the European Green Deal [1] which sets out a detailed vision to safeguard biodiversity, establish a circular economy and eliminate pollution. Further to this, in the Commission work programme for 2021, the revisions and initiatives linked to the European Green Deal climate actions and in particular the climate target plan's 55 % net CO_2 reduction target are presented under the ‘Fit for 55’ package [2]. The work programme included an important revision of the regulation setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles [3]. In the Commission’s work programme for 2022, the review of the CO_2 emission standards for heavy-duty vehicles has been included [4]. It is worth clarifying that both regulations for light- and heavy-duty vehicles are based on tailpipe emissions, what is known as Tank-to-Wheel (TtW).

The legislative landscape, with the review of such legislations and the challenges ahead to make Europe the first climate neutral continent by 2050, sets the scene for increased awareness and discussion on alternative pathways that will allow for substantial overall reduction of CO_2 emissions from road transport.

From the pollutant emissions’ perspective, significant efforts have been made in the past decades to reduce these emissions from internal combustion engines. Since the implementation of on-road testing for light- and heavy-duty vehicles in the legislation, pollutant emissions have been drastically reduced from these applications. In December 2020, the European Commission adopted the Sustainable and Smart Mobility Strategy (SSMS) [5]. The adopted strategy calls for more to be done: the upcoming proposal for stringent air pollutant emissions standards for combustion engine vehicles, Euro 7, will ensure that only future-proof ultra-low emissions vehicles come to the market.

The expected introduction of Euro 7 standards for light- and heavy-duty vehicles is intended to further reduce emissions significantly from heavy-duty vehicles with internal combustion engines in order to improve air quality on the roads and especially in cities.

This manuscript reports the pollutant and CO_2 emissions from a heavy-duty demonstrator vehicle with state-of-the-art emission control technologies tested with sustainable renewable fuels over a broad range of operations. The testing with sustainable renewable fuels was conducted within two phases of the AECC project. The emission control system used in phase 2 was updated with an active thermal management described in section 3. Well-to-Wheel (WtW) CO_2 emissions are reported.

The sustainable renewable fuels chosen for these tests were HVO and e-diesel. HVO was selected as an already available fuel at European service stations which is able to substantially reduce CO_2 in a WtW assessment. E-diesel was also tested. This fuel is expected to be available in the mid-term and will allow substantial CO_2 reductions provided that the hydrogen is produced from low carbon renewable energy and the CO_2 is captured from the atmosphere or from an unavoidable source.

2. Base vehicle and powertrain characteristics

The heavy-duty vehicle used in the project is an N3 Daimler Actros 1845 LS 4x2 tractor equipped with a 12.8 l engine with high pressure Exhaust Gas Recirculation (EGR) and homologated to Euro VI-C. The rated power of the engine is 330 kW at 1600 rpm and the type approval reference work in the World Harmonised Transient Cycle (WHTC) is 29.4 kWh.

3. Emission Control Technology system

Previous publications have described in detail the system implemented in phase 1 of the AECC heavy-duty demo vehicle project [6 - 8].

In the first phase of the project, the innovative emission control system was composed of a close-coupled (cc) DOC, SCR and Ammonia Slip Catalyst (ASC). The ccSCR/ASC is placed as the first component in the boxed system followed by a DOC, catalysed Diesel Particulate Filter and SCR/ASC, with twin AdBlue® injection and a hydrocarbon (HC) doser to support DPF regeneration. A novel twin AdBlue® dosing system was implemented to the demonstrator truck and controlled using FEV's in house developed twin dosing control software. The software controls both injection systems individually and coordinates the AdBlue® dosing. The system determines if the front or rear system should be used to optimise conversion efficiency.

In phase 2 of the project work, the emission control system was modified to further reduce cold-start emissions. The ccDOC which is located directly after the engine turbo and consists of two substrates was changed. An electrically heated catalyst (EHC) was implemented as the first substrate within the DOC canning, as can be seen in Figure 1.

In the phase 2 setup, the vehicle was fitted with an external 48 V system allowing for efficient use of the EHC and applying the power required when needed. The AC/DC converter installed in the vehicle supplied 10.8 kW maximum power, defining the EHC capacity.

The EHC was calibrated to hold a ccSCR temperature (front face) of 220 °C. At idle, EHC performance in the heavy-duty demonstrator truck is capable of achieving average gas temperatures downstream of the EHC between 350-400 °C and temperatures upstream of the ccSCR > 200 °C.

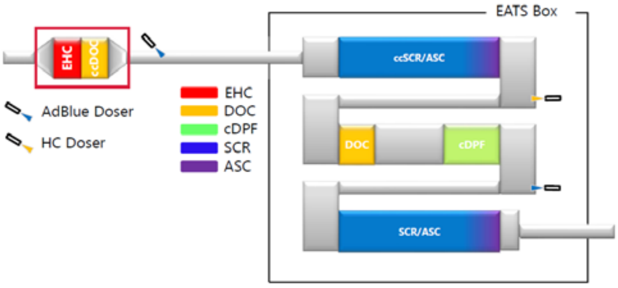

Figure 1. Phase 2 emission control system

The EHC supports the clean operation of the vehicle by reducing high NOx emissions from the cold-start and preserves the system temperature when the operating conditions include long idle phases. A dedicated paper on the phase 2 of the work is in the process of being published and for this reason the discussion in this manuscript will focus on the results achieved with the sustainable renewable fuels.

4. PEMS equipment integration

The emission results reported in this paper refer to tests conducted on the road with the vehicle instrumented with a Portable Emissions Measurement System (PEMS). To fully quantify both cold-start NOx emissions and secondary emissions compliance, a prototype PEMS was fitted to the demonstrator vehicle as shown in Figure 2. The tailpipe was modified to contain the Exhaust Flow Meter (EFM) for the PEMS kit and the equipment itself were set up on the trailer.

The PEMS kit contained NO (Chemiluminescence Detector) and NO_2 (Photoacoustic spectroscopy) analyzers to determine tailpipe NOx speciation, as well as CO and CO_2 measurement devices (Non-Dispersive Infrared Sensor). In addition to the gaseous measurements, PN10 is measured using a condensing particle counter (CPC).

Figure 2. PEMS installed in the vehicle

In addition to the standard PEMS equipment, the truck was fitted with portable NH_3 and N_2O measurement technology. N_2O was measured using a Non-Dispersive Infrared Sensor and the NH_3 was measured using a Quantum Cascade Laser setup.

5. Fuels

All measurements in project phases 1 and 2 have been done on EN 590 'B7' diesel fuel. Extra measurements were conducted on sustainable renewable fuels to validate the ultra-low pollutant emissions while significantly reducing Well-to-Wheel CO_2 emissions.

For the test with sustainable renewable fuels, in phase 1 of the project, the choice was to use 100% Hydrotreated Vegetable Oil. HVO is increasingly produced from waste and residue fat fractions coming from the food industry, as well as from non-food grade vegetable oil fractions. HVO could achieve up to 90% WtW CO_2 reduction straight from the pump depending on feedstock, this fuel meets the requirements of EN 15940 for paraffinic diesel fuels [9], for this reason, the calibration of the engine of the vehicle can be used without any adjustments.

Table 1. Fuel properties

Fuel property	Units	B7	HVO	e-diesel
Density	kg/l	0,835	0,78	0,7987
Cetane number		52	>70	74,8
Carbon content	%m/m	85,94	84,8	85,06
Hydrogen content	%m/m	13,35	15,2	14,94
Net heating value (m)	MJ/kg	42,74	43,6	43,91

During phase 2, an e-diesel was used to conduct on-road tests. The specifications of the fuel stayed within the limits of EN 15940 and therefore, no changes to the engine calibration were necessary.

Life Cycle Assessment (LCA) is an internationally standardised methodology (ISO 14040 ff), it helps quantifying the environmental footprint related to goods and services. For the moment, the LCA is not being used within the European regulatory framework to calculate CO_2 emissions from road-transport. Nevertheless, some companies and researchers are looking at such an approach to compare different technologies [10-12]. A first step towards LCA can be given by the well-to-wheel analysis.

In this paper, a WtW CO_2 analysis was conducted according to the JEC (JRC-Eucar-Concawe) methodology version 5 [13] and will be reported in the following section. The JEC methodology was chosen as its objective is to establish, in a transparent and objective manner, a consensual Well-to-Wheel energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2025 and beyond. Furthermore, current JEC version 5 is the first one including assessment data for heavy-duty vehicles.

$CO_{2,WtW}$ in g/km is calculated with equation (1) as described below.

$$CO_{2,WtT,fuel\ production}\left[\frac{g}{km}\right] - CO_{2,biocredits}\left[\frac{g}{km}\right] + CO_{2,TtW}\left[\frac{g}{km}\right] \tag{1}$$

The $CO_{2,WtT,fuel\ production}$ is calculated with equation (2).

$$\frac{Q_{fuel}\left[\frac{MJ}{100km}\right]}{100} * \left(\sum_{all\ compounds,i} CO_{2,intensity,WtT,i}\left[\frac{gCO_2}{MJ}\right] * NRJ_i\right) \tag{2}$$

Where Q_{fuel} is the measured fuel energy in MJ used by the vehicle for 100 km driven on the chassis dyno, $CO_{2,intensity,WtT,i}$ are the Well-to-Tank CO_2 emission factors for the compound i blended in the fuel, NRJ_i is the share of energy of the compound i blended in the fuel. The biocredits are calculated in a similar manner based on the value for each component blended in the fuel which is not from fossil origin.

An overview of all the data used is given in Table 2. Well-to-Tank (WtT) input data is coming from the JEC WtW report. Tank-to-Wheel input data is from on-road testing.

Well-to-Tank data from the JEC report is expressed in CO_{2eq} emissions as also the impact of other greenhouse gases is considered. This is not the case for the measured Tank-to-Wheel values.

Table 2. WtT data used on the WtW calculations

Fuel property	B7	HVO		e-diesel
		EU mix	Waste cooking oil	
$CO_{2\ intensity}$ (gCO_2/MJfuel)	73,73	71,31	71,31	71,03
WtT $CO_{2\ emission\ factor}$ (gCO_2/MJfuel)	18,20	30,00	11,10	0,81
$CO_{2\ biocredits}$ (gCO_2/MJfuel)	-5,03	-71,31	-71,31	-71,03

Note: JEC pathways chosen - B7: COD1+WOFA3a; HVO EU Mix.[14]; HVO Waste cooking oil: WOHY1a; e-diesel: RESD2.

6. On-road testing

On-road tests were defined to verify the broad range of driving conditions covered in the base project [6, 7] with conventional diesel.

Two routes were used, a typical In-Service Conformity (ISC) and an urban delivery route. The tests covered a significant range of the operating map of the engine. Speed profile of the routes can be seen in Figure 3.

Both route speed profiles are meant to replicate typical missions of the vehicle.

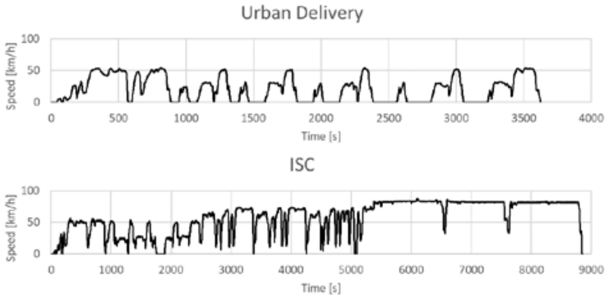

Figure 3. Speed profiles of the different routes completed

These routes ensure a broad coverage of the engine operating map as can be seen in Figure 4. The ISC test ensures a complete operation of the engine torque, including full load operation. The urban delivery route covers lower load operation compared to the ISC as it contains continuous 1, 2- and 3-minute stops where the engine is kept idling.

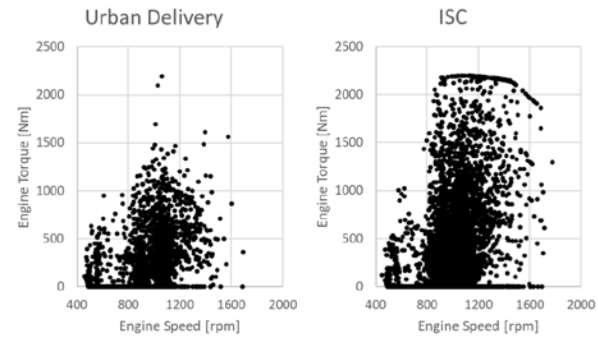

Figure 4. Operating engine map covered by the different routes completed

Similar to the base project, during the sustainable renewable fuel campaigns all tests were conducted with the vehicle preconditioned. Such preconditioning included running the vehicle at constant speed with high engine load to prepare the vehicle for the next day of testing. The protocol was implemented to investigate a severe condition for the emission control system. The preconditioning depletes the ammonia storage of both SCRs as well as passively regenerating the diesel particulate filter.

7. Results

A general remark on the results shown in this section is that the pollutant emissions figures include a summary of the emissions results of several tests. Error bars indicate the level of variability observed in the measurements. In particular, during the cold-start and the urban operation, there is a certain variability due to the impact of driving conditions and initial status of the emission control system.

The testing campaigns in phases 1 and 2 included different numbers of tests, ambient temperatures, payloads, and traffic conditions. Details on the conditions covered are reported below.

NOx emissions

A summary of the NOx emissions of the on-road test results obtained with the system with conventional diesel during phases 1 and 2 can be seen in Figure 5. The figure includes the results achieved by testing the vehicles with sustainable renewable fuels as well.

Phase 1 results show emissions from urban delivery and in-service conformity testing, focussing on the urban share of operation as emissions were near-zero in the other parts of the test. The on-road tests were conducted within a broad range of ambient temperatures from 4 to 25°C. With 10, 50 and 100% payload, as well as with an empty and a normally ammonia-loaded SCR.

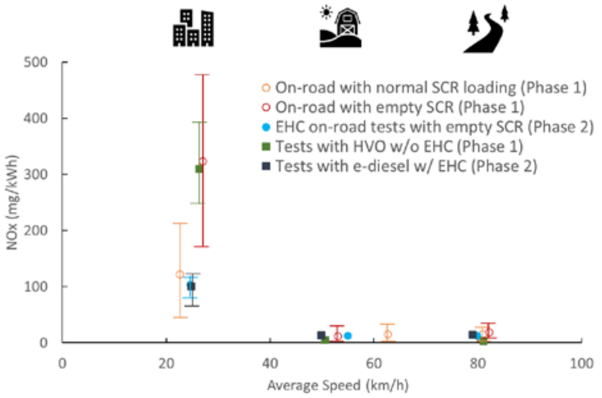

Figure 5. Summary NOx emissions of phase 1, phase 2 and testing with sustainable renewable fuels.

The on-road NOx emissions results with normal SCR ammonia loading are between 42 and 208 mg/kWh. For these tests, no preconditioning was conducted and the loading in the SCR at the beginning of the trip is how it remained at the end of the testing the previous day. On the other hand, results of on-road testing with empty SCR show a higher range of NOx emissions, from 168 to 475 mg/kWh. As can be seen, rural and motorway operation show very low tailpipe NOx values, all below 30 mg/kWh, as the emission control system is warm.

Figure 5 shows the range of emissions achieved in phase 2 of the project as well. As noted, at this stage the system includes the EHC. Tests were conducted with empty SCRs and with ambient temperatures between 5-8 °C. The NOx emissions under urban operation vary from 88 to 112 mg/kWh.

The tests conducted with HVO and e-diesel were similarly conducted with empty SCRs at the beginning of the trip. The HVO testing was conducted in phase 1 of the project. The results show the urban NOx emissions from 248 to 399 mg/kWh. The testing conducted with e-diesel in phase 2 of the project achieved urban NOx emissions from 65 to 137 mg/kWh. In both cases, this is within the variability observed in the results with market diesel. The rural and motorway emissions from the testing with sustainable renewable fuels are below 16mg/kWh.

Particulate number (PN10) emissions

A similar analysis was made for the particulate emissions. Phase 1 results show urban emissions with normal SCR loading from 6,07x10^{10} to 1,38x10^{11} #/kWh. Results from phase 1 with an empty SCR and a regenerated DPF show PN10 emissions varying from 1,74x10^{11} to 4,16x10^{11} #/kWh. The results of phase 2, with a system upgraded with the EHC, an empty SCR and regenerated DPF vary from 2,38x10^{10} to 1.34x10^{11} #/kWh.

HVO on-road tests from phase 1 show results varying from 2,86x10^{11} to 5,37x10^{11} #/kWh. In addition, the testing with e-diesel conducted on phase 2 of the project achieved 9,88x10^{10} to 1,03x10^{11} #/kWh. In both cases, this is within the range observed on market diesel.

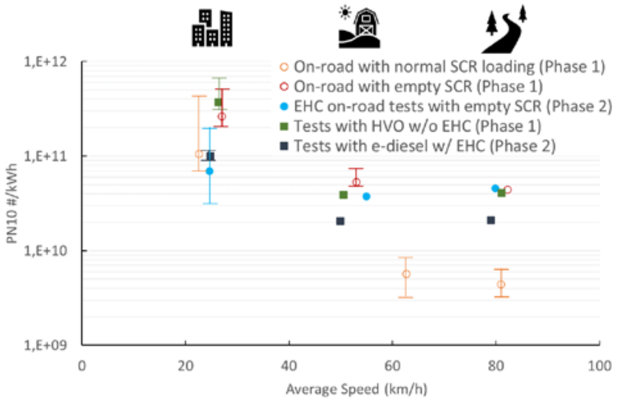

Figure 6. Summary of PN10 emissions of phase 1, phase 2 and testing with sustainable renewable fuels.

Ammonia (NH_3) and nitrous oxide (N_2O) emissions

As described in section 4, the vehicle was equipped with a PEMS system able to measure NH_3 and N_2O. In general, all tests conducted in phases 1 and 2 showed extremely low ammonia emissions. This is mainly due to the system being equipped with ammonia slip catalysts after each SCR. Phase 1 results have been published and can be found in previous publications [6 - 8].

Regarding N_2O emissions, these emissions occur due to unselective catalytic reactions within the DOC or even the ammonia slip catalyst via unselective oxidation of unreacted NH_3. As previously reported [6 – 8], the N_2O is produced throughout the length of the trips. Figure 7 shows the summary of N_2O emissions for phases 1 and 2 of the project. The resulting urban emissions from on-road testing with normal SCR loading on phase 1 of the project vary from 58 to 78 mg/kWh. In rural operation the N_2O emissions varied from 42 to 68 mg/kWh and in motorway operation from 27 to 40 mg/kWh. The N_2O urban emissions achieved with an empty SCR in phase 1 varied from 18 to 59 mg/kWh, rural emissions from 19 to 37 mg/kWh and in motorway driving from 16 to 58 mg/kWh.

In phase 2, the urban N_2O emissions achieved with an empty SCR ranged from 65 to 87 mg/kWh, with the ISC test achieving rural N_2O emissions of 25 mg/kWh and 47 mg/kWh in motorway operation.

N_2O urban emissions from the testing with HVO in phase 1 vary from 54 to 106 mg/kWh. There was one in-service conformity test with N_2O urban emissions of 196 mg/kWh. This test is considered an outlier and further analysis need to be conducted to understand what could have caused these higher N_2O emissions. The N_2O urban emissions from the e-diesel testing in the project's phase 2 vary from 89 to 106 mg/kWh.

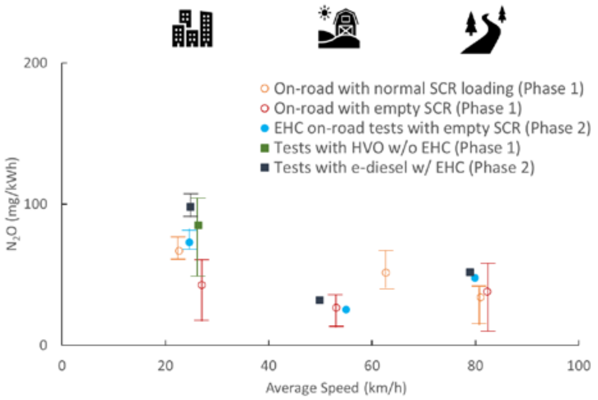

Figure 7. *Summary of N_2O emissions of phase 1, phase 2 and testing with sustainable renewable fuels.*

Well-to-Wheel CO_2 emissions reductions

From the beginning of the project, the intention was to implement an emissions control system which would impact as low as possible the WtW CO_2 performance of the vehicle. Phase 1 of the project kept this impact to less than 3% on average. For phase 2, the calculation of the fuel consumption/CO_2 included in Figures 8 and 9 does not include the power required to use the EHC. This is the case for both diesel and e-diesel calculations, so it is not impacting the fuel comparison. However, the external power required for the EHC to be used within an in-service conformity test has been calculated to be about 1%.

It is important to note that the CO_2 emissions vary within the on-road tests due to the many factors found on the road, including traffic conditions, ambient temperature, road closures or driver dynamics. The average of the CO_2 emissions of the tests has been identified as the best approach to compare the results.

Figure 8 shows the average Tank-to-Wheel CO_2 emissions of urban and in-service conformity tests at ambient temperatures between 4 to 23 °C. All tests have been conducted with 10% payload, as the data available for this condition was larger.

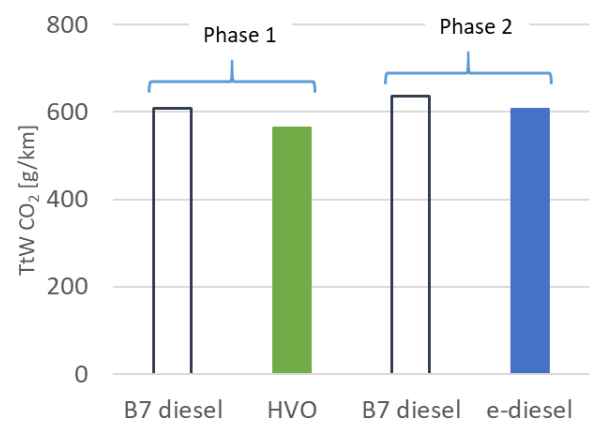

Figure 8. Average TtW CO_2 emissions of urban and in-service conformity tests with conventional and sustainable renewable fuels

Figure 9 shows the results of the Well-to-Wheel CO_2 emissions from the analysis conducted using the JEC version 5 methodology and pathway assumptions [11]. The WtW methodology estimates the energy use and GHG emissions in the production of a fuel and its use in a vehicle. Results show substantial WtW CO_2 reductions can be obtained by using this approach.

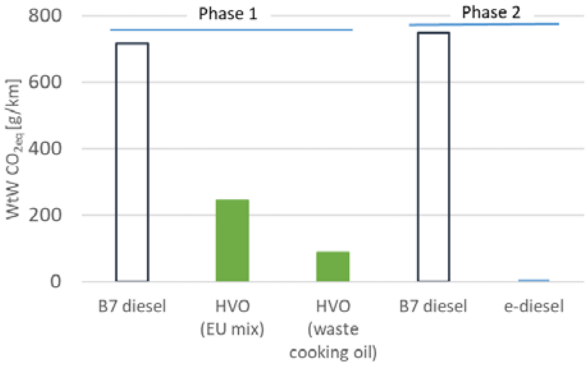

Figure 9. WtW CO_2 emissions reductions

Results show that HVO can reduce the WtW CO_2 emissions up to 89% with respect to B7 diesel if the feedstock used is waste cooking oil. Using the HVO mix found within the EU reduces the emissions up to 70%.

E-diesel used within the current study achieves 99% WtW CO_2 emissions reduction.

8. Conclusions

This work summarised the ultra-low pollutant and Well-to-Wheel (WtW) CO_2 emissions of an demonstrator N3 (long-haul) vehicle with an advanced emission control system and in 2 project phases.

The vehicle was equipped with a state-of-the-art emission control system including close-coupled components. The vehicle was tested with conventional and sustainable renewable fuels and all data presented relates to on-road testing.

The results show ultra-low pollutant emissions on the vehicle in both phases of the project.

While significant cold-start NOx emissions reductions are achieved in phase 2 of the project, the phase 1 system (without the EHC) already achieves very low NOx emissions when the SCR systems are used with normal ammonia load at the beginning of the test.

PN emissions for all cases are very low. However, test results indicate that cold-start remains the main event for the particulates. These pollutant emissions reductions are confirmed when the vehicle is tested with sustainable renewable fuels.

Furthermore, regarding WtW CO_2 emissions, results show significant reductions can be achieved by the use of sustainable renewable fuels. It is important to note that HVO is already available in several European countries and such WtW CO_2 emission reductions can be achieved by the current in-use vehicle fleet. The e-diesel shows potential for further reductions almost reaching CO_2 neutrality on a WtW basis.

Based on the ultra-low pollutant emissions achieved through the combination of close-coupled catalysts as well as the use of sustainable renewable fuels contributing towards very low WtW CO_2 emissions, internal combustion engined heavy-duty vehicles will continue to support a sustainable European economy for the next decades.

9. Acknowledgement

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