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Ultra-Low Emissions from a Truck with Close-Coupled Emission Control System and Active Thermal Management using e-Fuels

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Abstract

The European economy requires that materials and goods be distributed by heavy-duty vehicles both on the countryside and within our cities every day. These vehicles need to be clean and efficient to comply with expected stringent future pollutant emissions and demanding CO_2 standards. On the pollutant side, the upcoming new Euro 7 regulation will likely focus on ensuring the emissions from heavy-duty vehicles are minimized over extensive on-road operating conditions and in particular in urban driving including cold-start operation. These challenges are increased by the need to ensure low NH_3 and N_2O emissions as well.

This study shows ultra-low pollutant emissions achieved by a heavy-duty diesel demonstrator vehicle over a broad range of operating conditions. Previous work indicated what a close-coupled emission control system including dual-SCR could achieve. In this paper, the results obtained by the integration of active thermal management to the system are discussed including further improvement of cold-start and urban operation emissions. Also, avoidance of emission slip after stop periods with idling engine are investigated. The innovative emissions control system implemented on the truck integrates a close-coupled DOC, including an electrically heated catalyst (EHC), a catalysed DPF, a dual-SCR system -one in a close-coupled position-, with twin AdBlue® dosing. Both SCR catalysts contain an ammonia slip catalyst.

Pollutant emissions were evaluated over a broad range of operating conditions to investigate the emissions reduction potential. The vehicle was instrumented with a prototype PEMS measuring NH_3, N_2O and PN10 emissions.

The vehicle has also been tested with sustainable renewable fuels, including a novel e-diesel, to show the potential CO_2 reduction on a Well-to-Wheel (WtW) basis. The results of a simulation study investigating the outlook of NOx vs CO_2 behaviour considering 2025 and 2030 prospective engines including hybridisation has been included.

This should enable the next generation heavy-duty vehicles to operate with ultra-low emissions, whilst maintaining their path towards the required CO_2 targets.

Content

1 Introduction

Heavy-duty vehicles move tonnes of goods everyday within Europe. In 2020, the COVID-19 pandemic broke the upward trend seen in recent years in the EU road freight transport when it showed a 0,9% reduction from 2019 to 2020, culminating the increase by 3.2% from 2018 to 2019 [1]. It is expected the growing trend will return in 2022. These trucks travel on European highways and in cities, and therefore it is essential these vehicles are clean and efficient. Euro emission standards have consistently reduced pollutant emissions of these vehicles over the past decades. In particular, Euro VI emission standards [2] for heavy-duty vehicles entered into force in January 2013 have successfully and significantly reduced on-road NOx emissions and particulates. This is mainly observed by the introduction of a Portable Emission Measurement System (PEMS) demonstration test at type approval, combined with on-road in-service conformity testing which allows for comprehensive analysis of the emission performance of these vehicles while driving on public roads. The latest Euro VI step E [3], applicable for new vehicles registered from the beginning of 2021, ensures that for the first time, the cold-start emissions are included in the emissions analysis during on-road testing. In addition, a limit has been introduced for the solid particulate number (PN) measured with PEMS.

The on-road tests prescribed by the regulation today have strict requirements. However, these do not fully cover all driving conditions trucks encounter frequently on the road. Some conditions are not well covered by the current procedure prescribed to analyse the emissions data to determine compliance of the vehicle, in specific, operating conditions where current exhaust emission control system will potentially cool down and lose conversion efficiency like urban operation. This has been studied and discussed in detail in the literature [4].

It is expected that the European Commission will present new Euro 7 emission standards for light- and heavy-duty vehicles proposal in the third quarter of 2022. This Euro 7 proposal will then be considered by the European Parliament and European Council within an ordinary legislative procedure. As such, the European Commission began the process of reviewing the emissions standards for cars, vans, trucks, and buses in 2018. The Commission established the Advisory Group on Vehicle Emission Standards (AGVES) and contracted the CLOVE (Consortium for ultra LOw Vehicle Emissions) with the scope to study the current legislation and develop possible legislative scenarios [6]. The objective expressed by the European Commission is to ensure clean vehicles throughout their expected lifetime measured in real-world driving. The expected introduction of Euro 7 standards is intended to further reduce emissions significantly from heavy-duty vehicles with internal combustion engines to improve air quality on the roads and especially in cities.

This paper summarises the findings of a project set up to investigate improvement potential in emission control over the full operational window of a truck. The project includes two phases of work. In Phase 1, the original emission control system of the vehicle was substituted with a new one, including close-coupled catalysts and twin AdBlue® injection. The system was calibrated for enhanced NOx conversion finding an optimized AdBlue® dosing profile to achieve lowest emissions of NH_3 and N_2O [7]. In Phase 2, the system was upgraded to include active thermal management in the form of a close-coupled electrically heated catalyst (EHC) [8]. The project achieved ultra-low levels of emissions over a wide range of driving conditions. These ultra-low pollutant emissions results were confirmed and validated with two sustainable renewable fuels, being Hydrotreated Vegetable Oil (HVO) and e-diesel [11].

Further to the work completed with the heavy-duty demonstrator vehicle, a series of simulations were performed as an outlook for NOx vs CO_2 emissions behaviour of a heavy-duty vehicle using an emission control system as the one included in the heavy-duty demonstrator and considering possible 2025 and 2030 engines, including hybridisation.

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 system

In the first phase of the project, the innovative emission control system was composed by a close-coupled (cc) DOC, SCR and Ammonia Slip Catalyst (ASC). The close-coupled components were followed by a second DOC, a catalysed Diesel Particulate Filter (cDPF) and at the end of the tailpipe a second SCR with ASC. The system included a twin AdBlue® injection and a hydrocarbon (HC) doser to support DPF regeneration. The implementation of the first phase system as well as detailed results have been reported previously [7].

In the second phase of the project, the emission control system was modified to further reduce cold-start emissions. The ccDOC, located directly after the engine turbine and composed by two substrates, was modified. An electrically heated catalyst (EHC) was implemented as the first substrate within the DOC canning. The phase 2 setup can be seen in Figure 1. During the phase 2, the vehicle was fitted with an external 48 V system allowing the efficient use of the EHC by applying the power required when needed. The AC/DC converter installed in the vehicle supplied 10.8 kW maximum power, defining the EHC heating 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 was capable of achieving average gas temperatures downstream of the EHC between 350-400 °C and temperatures upstream of the ccSCR > 200 °C.

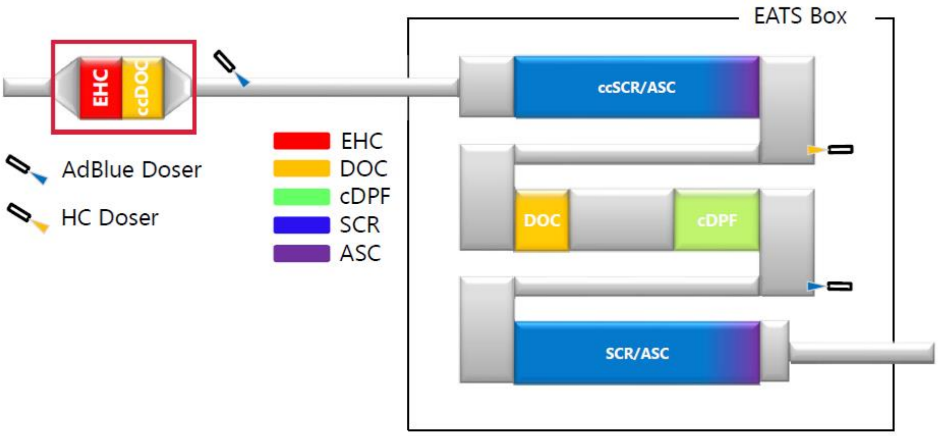

Fig. 1 Emission control system, phase 2.

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. Details of the implementation of the EHC into the system have been published recently [10].

4 Vehicle emission measurement instrumentation

The pollutant emissions were measured on-road with Portable Emissions Measurement System (PEMS). An enhanced PEMS was fitted to the demonstrator vehicle as shown in Figure 2.

The PEMS kit contained NO (Chemiluminescence Detector) and NO_2 (Photoacoustic spectroscopy) analysers 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 measurement equipment was also fitted. There were no intermediate PEMS emission measurements points. The intermediate measurements for NOx and NH_3 were possible through dedicated sensors. In addition to the standard equipment, the truck was fitted with both 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. Further details of the system can be found in previous publications [7].

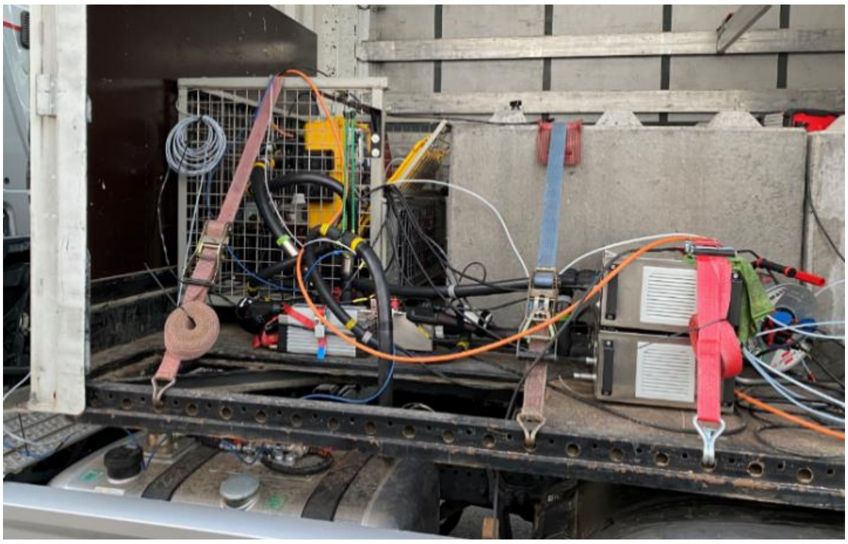

Fig. 2 PEMS installed in the vehicle.

5 On-road tests

During the two phases of the heavy-duty project different on-road tests were conducted. The results shown in this paper concentrate on two on-road routes used in both phases of the work and which were also used to validate the ultra-low pollutant emissions with sustainable renewable fuels. The routes cover a typical in-service conformity trip (as prescribed by Euro VI regulation) and an urban delivery route. The tests covered a significant range of the operating map of the engine, including different payloads. The speed profiles of these routes can be seen in Figure 3.

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

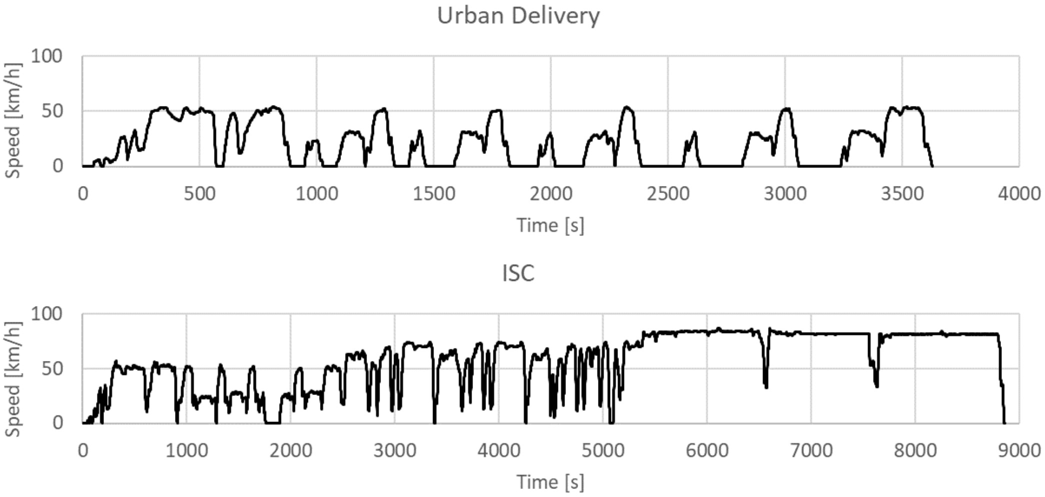

Fig. 3 Speed profiles of the urban delivery and the in-service conformity routes.

During phases 1 and 2 of the project, some 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. This protocol was implemented to investigate severe conditions for the emission control system. The preconditioning depletes both SCR’s ammonia storage as well as passively regenerates the DPF.

6 Ultra-low pollutant emissions

6.1 NOx emissions overview

The summary of NOx emission results obtained during the different testing campaigns completed by the AECC heavy-duty diesel demo vehicle is shown in Figure 4. These results have been reported in previous publications for phase 1 [7] and phase 2 with the active thermal control [10].

The NOx results achieved after implementing the active thermal management are included in Figure 4 as well as the results of the phase 1 of the project which have been left for reference. Phase 2 tests, were conducted with empty SCRs at the beginning of the trip and within an ambient temperature of 5 to 8 °C. The resulting NOx emissions vary from 88 to 112 mg/kWh during urban operation. These emissions are lower than the lowest result from previous testing with empty SCR tests.

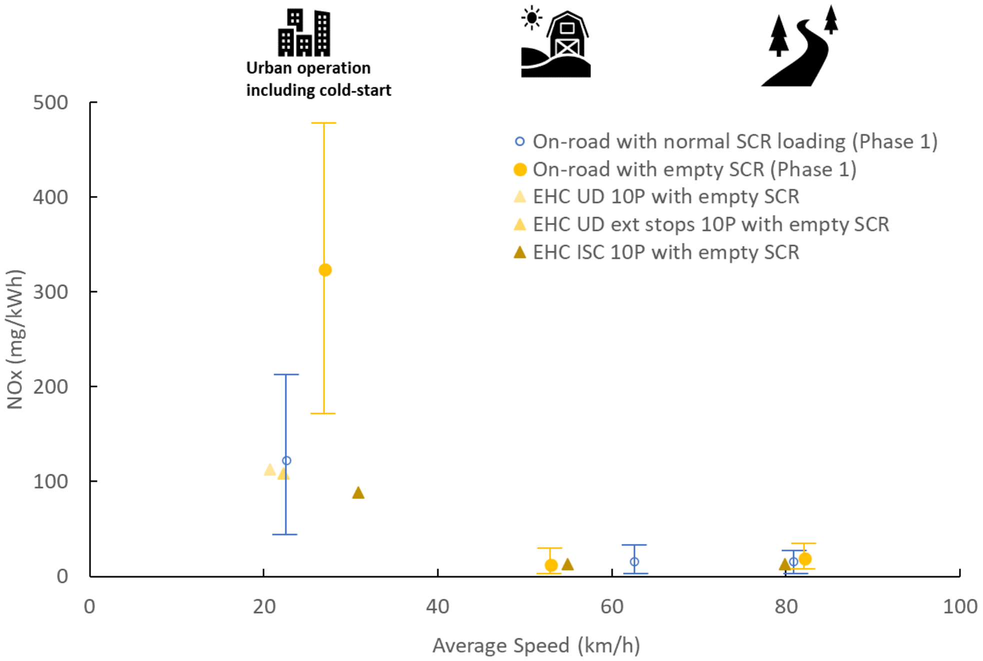

Fig. 4 Summary of NOx emissions obtained throughout the AECC heavy-duty diesel vehicle project.

Testing with the support of the electrically heated catalyst delivers a significant decrease of cold-start emissions regardless of the performed trip.

Figure 5 shows the comparison between an urban delivery test with and without EHC during the first 600 s of operation. The test with the EHC results is represented by solid lines. The temperatures upstream of the ccSCR and the box SCR are plotted. As can be seen, when using the EHC, the ccSCR reaches ~200 °C in a shorter period (~60 s). The ccSCR layout is already allowing the system to heat up quickly but with the EHC addition, the heat-up period is further decreased. The figure shows the release of the AdBlue® and further down the NOx emissions downstream of the ccSCR can be seen, as well as the NOx in the tailpipe. Further to these, the figure includes the power required by the EHC to heat the system up in these initial 600 s, as well as the exhaust mass flow passing through the pipes which will influence the heat required.

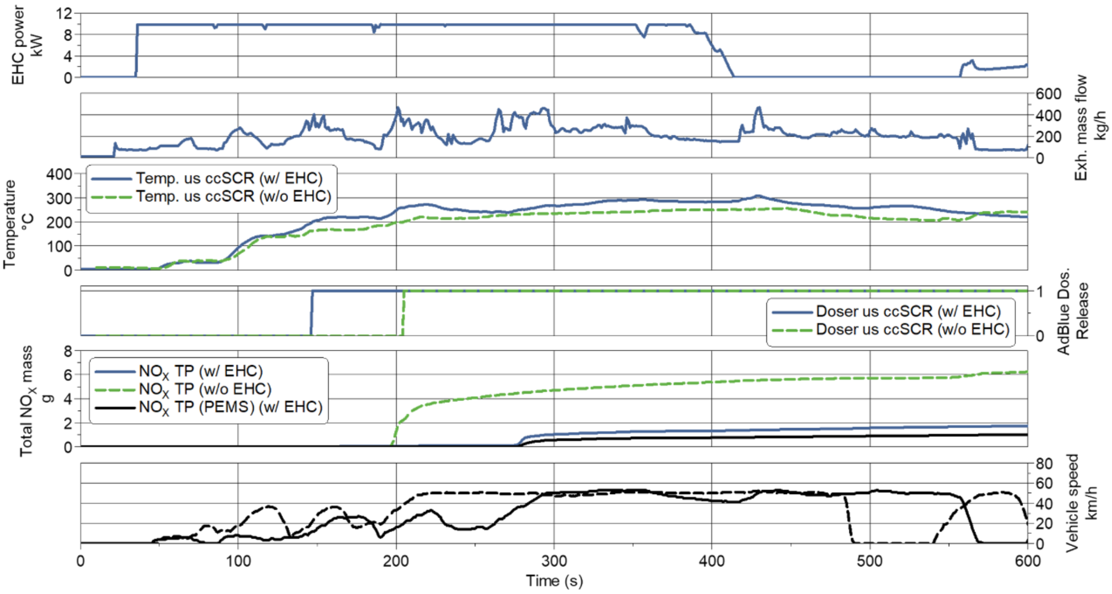

Fig. 5 Initial 600 seconds of the Urban delivery route NOx emissions.

In the urban driving route, the use of the EHC and the NOx storage effect resulted in ~70% tailpipe NOx reductions during the first 600 s, and 67% reduction in the whole trip compared to a similar test conducted without EHC.

Figure 6 shows the impact of the EHC in keeping the ccSCR within the target temperature during a dedicated urban delivery trip with extended stops of 2, 4 and 6 minutes.

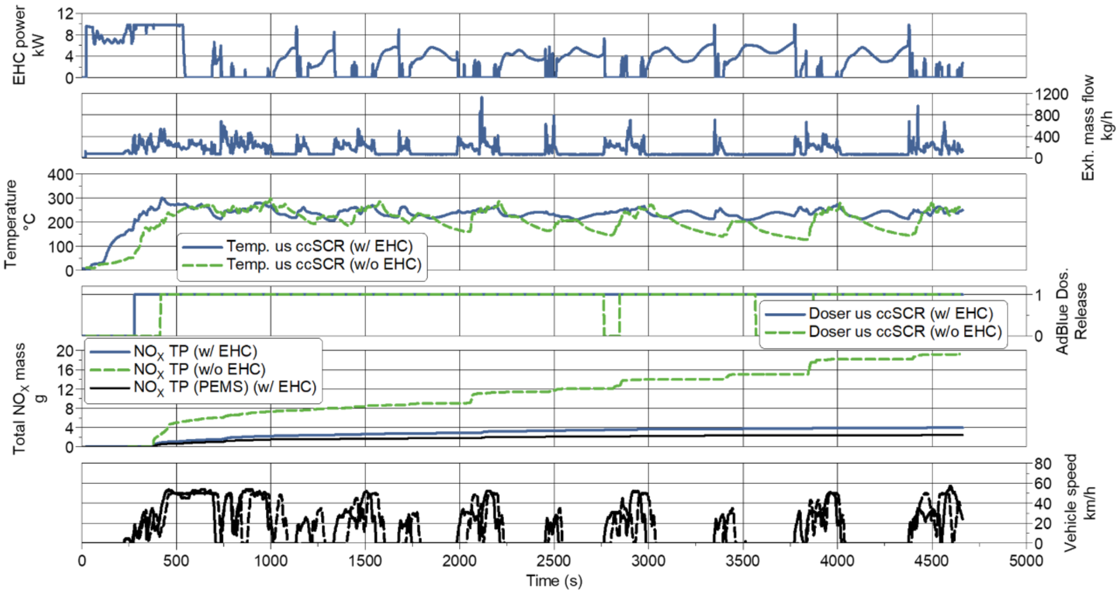

Fig. 6 Effect of EHC operation on keeping the ccSCR within the target temperature of 220 °C within an urban delivery trip

The emission slip which occurred at the tailpipe during the first acceleration after these stops without EHC (at around 2000 s, 2750 s, 3400 s and 3600 s) is no longer present with EHC implemented.

It is important to note that the NOx concentration profiles in Figure 5 and 6 show a delay in respect to the start of the initial cold-start peak. This is attributed to NOx absorption in the water inside the SCR, which desorbs at the point the SCR reaches its operating temperature, generating the initial NOx emissions peak.

6.2 Particulate number (PN10) results

A summary of the particulate number (PN10) results obtained during phases 1 and 2 tests are presented in Figure 7. The particulate emissions have been measured by the PEMS installed on the vehicle. The particulate number is reported as measured without considering any measurement uncertainty. Crankcase emissions have not been considered in the results.

Similarly to what has been described for the gaseous emissions, the results from the phase 1 of the project are kept on Figure 6 for reference. Results show PN10 emissions from the phase 2 testing (with empty SCR and regenerated DPF) varying from 2.38x10^{10} to 1.34x10^{11} #/kWh.

The phase 2 system single ISC result in rural operation is 3,78x10^{10} #/kWh. Within the motorway operation, the phase 2 system emitted 4,60x10^{10} #/kWh.

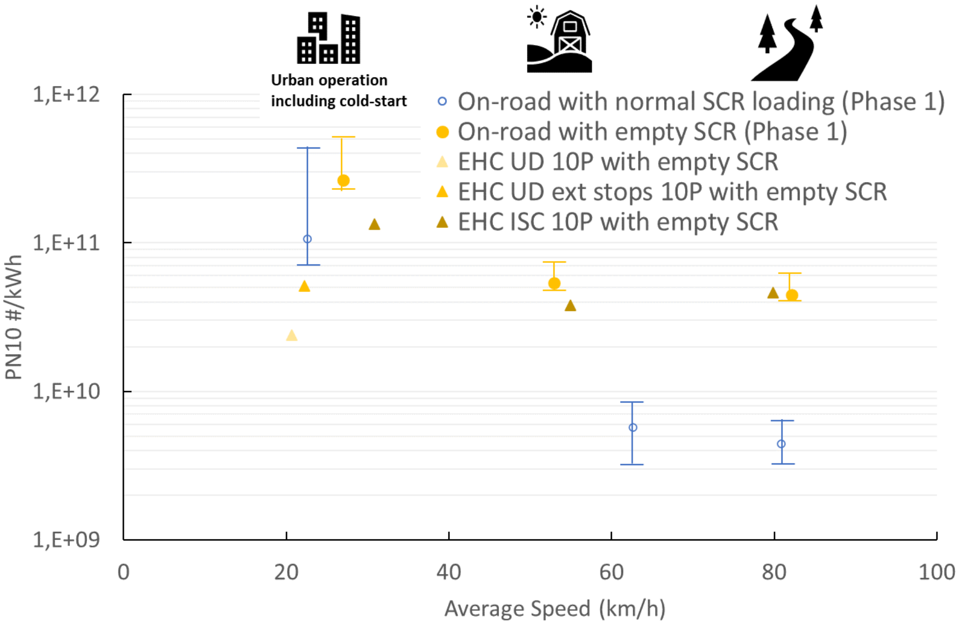

Fig. 7 Summary of PN10 emissions obtained throughout the AECC heavy-duty diesel vehicle project

6.3 Ammonia (NH3) and nitrous oxide (N2O) emissions

Ammonia emissions have been measured and reported in detail in previous publications for phases 1 and 2 [7]. Overall, through the two project phases, the results are very low. Ammonia emissions can be generated by an overdose of AdBlue®, however the system is equipped with ammonia slip catalysts after each SCR. During the tests conducted, the ammonia results have shown an excellent slip control from the emissions control system.

Figure 8 shows a summary of the N_2O emissions. Results with and without EHC are within the same level as previous reported. N_2O formation can be related to the occurrence of unselective catalytic reactions within the DOC or even the ASC via unselective oxidation of unreacted NH_3. Results from phase 1 have been left for reference as done for NOx and PN above. Results show N_2O emissions from the phase 2 testing (with empty SCR and regenerated DPF) varying from 65 to 87 mg/kWh. The phase 2 system single ISC result in rural operation is 25 mg/kWh. Within motorway operation, phase 2 system emitted 47 mg/kWh. The EHC implementation had no significant effect on the production of this greenhouse gas.

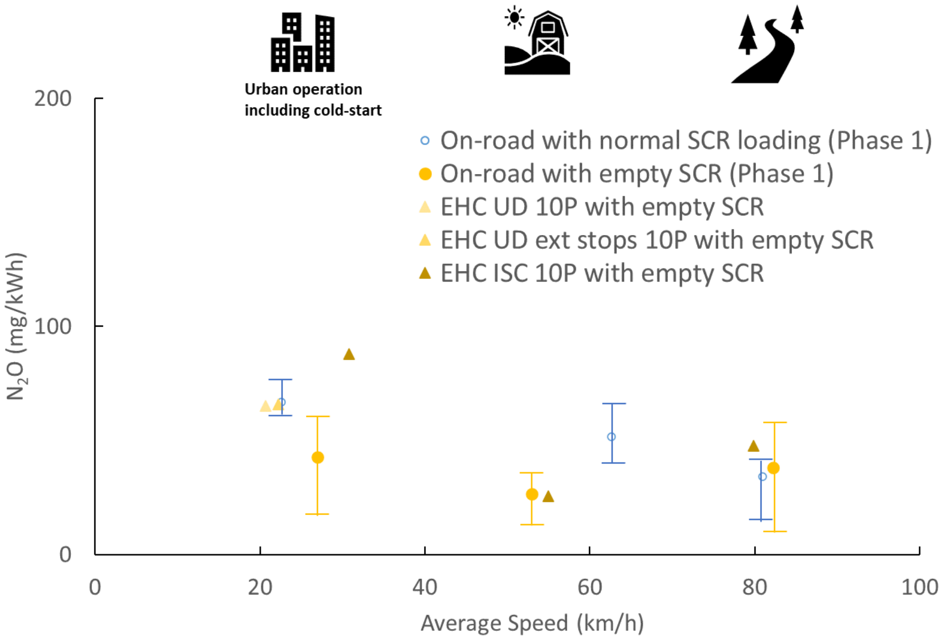

Fig. 8 Summary of N_2O emissions obtained throughout the AECC heavy-duty diesel vehicle project.

7 Ultra-low emissions on sustainable renewable fuels

7.1 Fuels

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

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 [12], and for this reason, the calibration of the engine of the vehicle can be used without any adjustments.

During phase 2, an e-diesel was used to conduct on-road tests. The specifications of the fuel (included in Table 1) stayed within the limits of EN 15940 and therefore, no changes to the engine calibration were necessary.

Tab. 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

7.2 Pollutant emissions from sustainable renewable fuels testing

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 urban NOx emissions vary 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 16 mg/kWh.

Regarding PN10 emissions, HVO on-road tests from phase 1 show results varying from $2,86 \times 10^{11}$ to $5,37 \times 10^{11}$ #/kWh. In addition, the testing with e-diesel conducted on phase 2 of the project achieved $9,88 \times 10^{10}$ to $1,03 \times 10^{11}$ #/kWh. In both cases, this is within the range observed on market diesel.

Finally, similarly to the testing with conventional diesel, ammonia has been extremely low while the vehicle was tested with sustainable renewable fuels. The 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.

8 NOx vs CO2 emission behaviour of the heavy-duty demonstration truck

8.1 Well-to-Wheel CO2 emissions reductions

An important aspect to highlight is the effect that the implementation of the emission control system in the demonstrator vehicle had on its CO_2 emissions performance. During the simulation performed prior to the build-up of the emission control system of phase 1, the back-pressure of the new system was calculated. An increase of the back-pressure compared to the original system was expected caused by additional components including the ccDOC, the AdBlue® mixing element and the ccSCR. The final system showed less increase in back-pressure than conservatively assumed. An overall increase in CO_2 emissions of ~3% could be observed during the ISC tests with 10% payload compared to reference measurement data from the truck with the original exhaust line.

In the project's phase 2, the integration of the EHC included the implementation of a 48 V external system to provide the power needed for the operation of the EHC, meaning that the power used by the EHC was measured externally. In this case, it was possible to calculate the impact on the truck's fuel consumption by calculating the power used by the EHC back to fuel consumed. The energy consumption varied between 1.03 (ISC) and 4.2 (urban delivery) kWh respectively. The calculated additional fuel consumption based on the energy consumption depends on the averaging distance. For example, for the ISC, 1% additional fuel consumption is calculated compared to the phase 1 system, for an achieved 60% reduction in NOx. Please note the reported calculated additional fuel consumption is an indication as further improvement can be expected for a future implemented 48V board net with smart energy management.

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.

To compare the CO_2 emissions in a comprehensive manner, a WtW CO_2 analysis was conducted according to the JEC (JRC-Eucar-Concawe) methodology version 5 [13]. The detailed WtW calculations for the heavy-duty demonstrator results were included in a recent publication [11]. Figure 9 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.

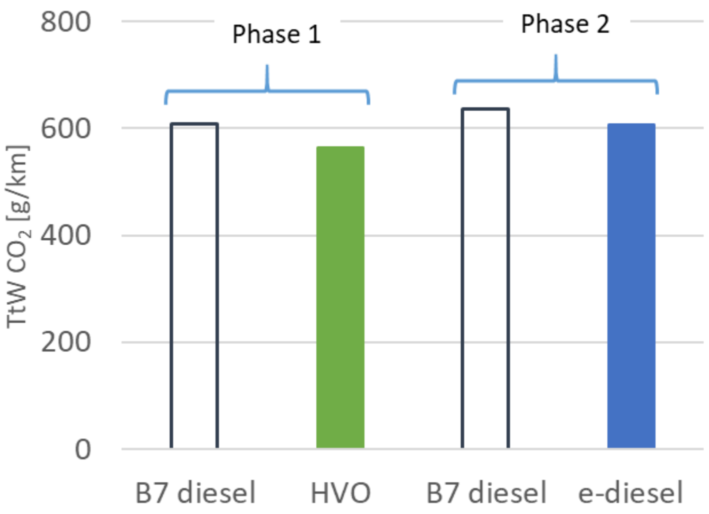

Fig. 9 Average TtW CO_2 emissions of urban and in-service conformity tests with conventional and sustainable renewable fuels.

Figure 10 shows the results of the Well-to-Wheel CO_2 emissions from the analysis conducted using the JEC version 5 methodology. 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.

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.

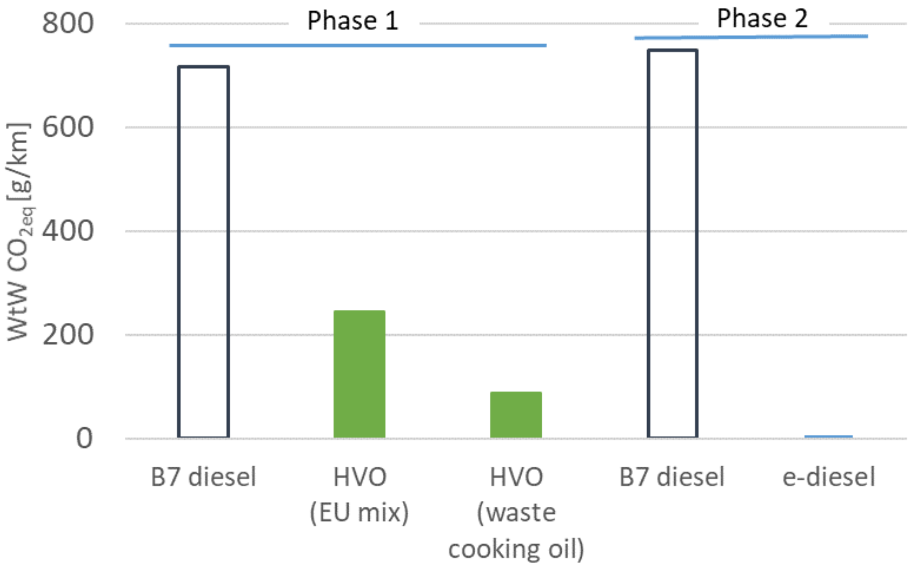

Fig. 10 WtW CO_2 emissions reductions.

8.2 Simulated NOx vs CO2 behaviour with 2025 and 2030 engines

The work completed with the demonstrator was used as the base model for investigating the simulated NOx vs CO_2 emission behaviour of a truck considering possible 2025 and 2030 engines including a hybrid powertrain. The specifications of the simulated powertrains are included in Table 2.

Tab. 2 Simulated powertrain general specifications.

	2025 powertrain	**2025 P2 hybrid**	**2030 powertrain**	**2030 P2 hybrid**
Low NOx mode (~2 g/kWh)	✓	✓	✓	✓
High efficiency mode (~5-8 g/kWh)	✓	✓	✓	✓
FEV 55% BTE engine			✓	✓
Increased peak firing pressure and compression ratio			✓	✓
Improve boosing system, friction layout and combustion system			✓	✓
Waste Heat Recovery			✓	✓
P2 hybrid system		✓		✓

The P2 hybrid system considered for the simulations is shown in Figure 11. The system has a clutch between ICE and E-Motor to make e-drive possible, ensure high recuperation potential and high powertrain efficiency. The used E-Motor has a peak power of 120 kW and a continuous power of 80 kW.

For the simulation, an in-service conformity cycle based on the on-road cycle conducted during the phases 1 and 2 testing was used as well as VECTO long haul cycles for 10 and 100% payloads.

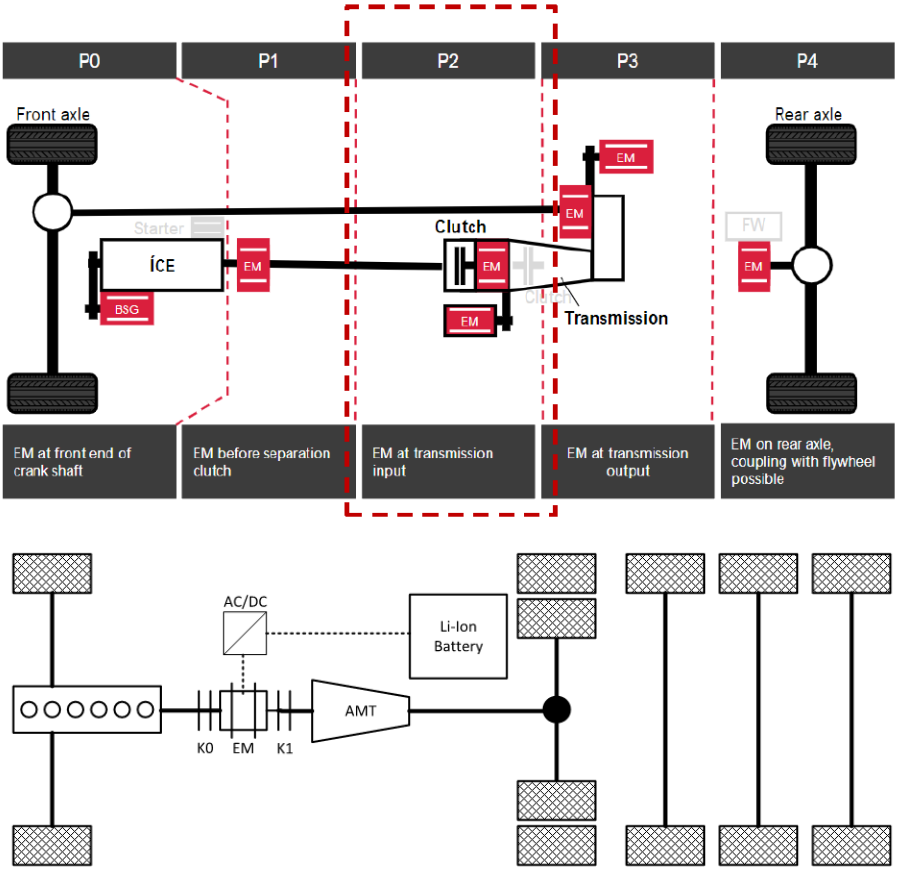

Fig. 11 P2 hybrid system considered for the 2025 and 2030 simulations.

The NOx tailpipe simulation accuracy achieved was +/-30%. Normally the accuracy expected on such a simulation should be +/-10%. In this case the very low level of the emissions in some areas of the simulated trips and the lack of catalyst characterization data for the model setup had an impact on this aspect. The model setup was done only based on PEMS measurements. The CO_2 emission simulation accuracy was within +/-1.5%.

Engine-out emissions considered for the 2025 and 2030 powertrains are shown in Figure 12. With a 2030 engine using advanced fuel saving technologies a CO_2 emission benefit of 8 to 9% could be reached. In this case, the engine out emissions increase will challenge the emission control system as shown in Figure 13. However, the results show that all 4 combinations can achieve ultra-low NOx emissions at the tailpipe with the advanced emission control system despite the engine-out emissions increase.

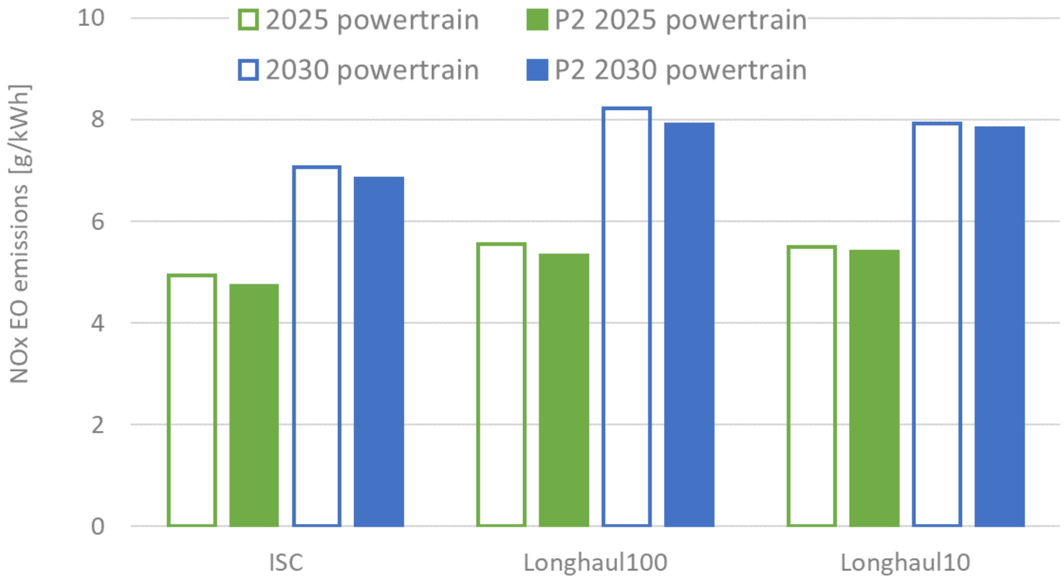

Fig. 12 Average engine-out NOx emissions of simulated trips.

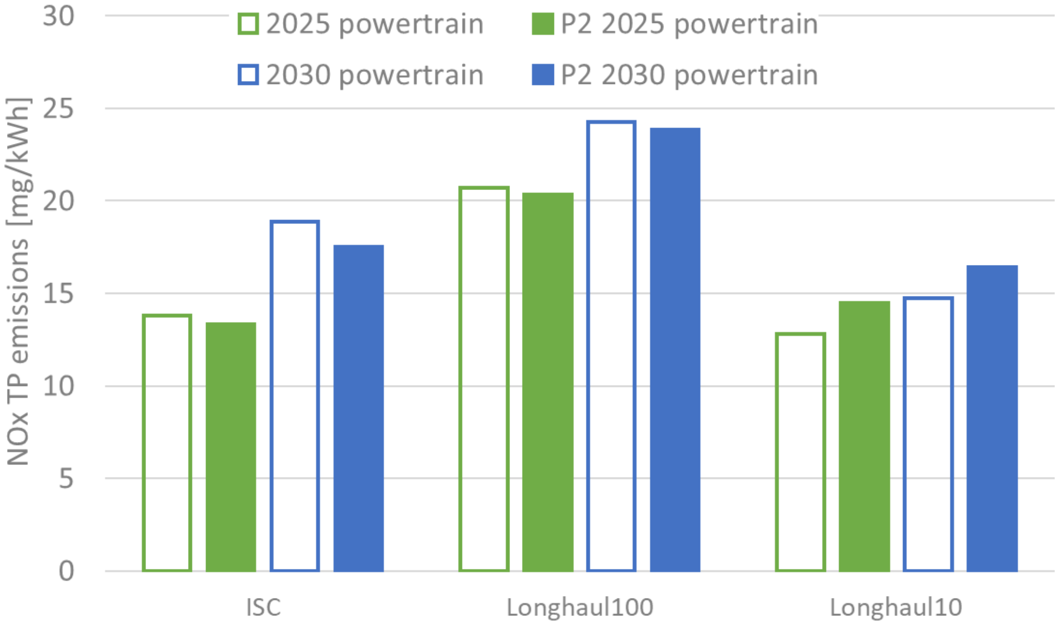

Fig. 13 Average tailpipe NOx emissions of simulated trips.

The P2 hybrid can bring an additional 3 to 6% fuel saving potential. Finally, combining a 2030 engine and a P2 hybrid system CO_2 improvements of 11 to 14% can be reached depending on the driving conditions as shown in Figure 14.

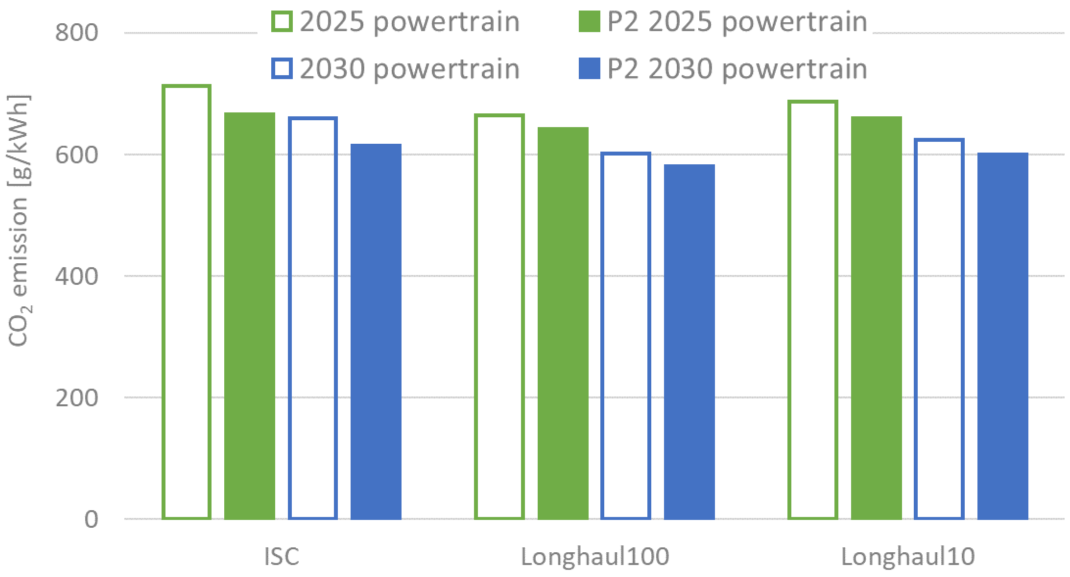

Fig. 14 Average CO_2 emissions of simulated trips.

9 Conclusions

This paper summarised the ultra-low pollutant emissions of the 2 project phases of a demonstrator N3 (long-haul) vehicle with an advanced emission control system. The vehicle was equipped with a state-of-the-art emission control system including close-coupled components in phase 1 and including active thermal management for phase 2. The vehicle was tested with conventional and sustainable renewable fuels.

The results show ultra-low pollutant emissions on the vehicle in both phases of the project. Phase 1 system achieves very low NOx emissions and further cold-start NOx emissions reductions are achieved in phase 2 of the project. 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.

As can be seen for the NOx vs CO_2 simulation work, further NOx and CO_2 reductions can be expected with 2025 and 2030 engine combustion technology improvements combined with modern emission control technologies. It is important to note that based on the calculations presented, significant reduction on Well-to-Wheel CO_2 emissions can be obtained by using novel sustainable renewable fuels.

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

10 Acknowledgements

The authors would kindly like to thank the members of AECC for supplying the catalyst and filter parts and for their highly valuable contributions to this study; as well as the International Platinum Group Metals Association (IPA) and Corning Inc. for the financial support. We also like to thank NESTE and Aramco for supplying the sustainable renewable fuels for this study. Thanks to Daimler Trucks for providing the basic production truck and FEV for their continuous support during the development of this project.

11 Abbreviations

ASC	Ammonia Slip Catalyst
cc	close coupled
CO	Carbon monoxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
HC	Hydrocarbons
ICE	Internal combustion engine
MAW	Moving Average Window
NDIR	Non-dispersive Infrared
NOx	Nitrogen oxides (refers to the sum of NO and NO_2)
PEMS	Portable Emission Measurement System
SCR	Selective Catalytic Reduction

12 References

[1] Road Freight Transport Statistics: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_statistics

[2] Commission Regulation (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council

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