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Executive Summary

The joint project "Robust and Efficient Processes and Technologies for Drop-In Renewable Fuels for Road Transport" (REDIFUEL) aims to produce an ultimate renewable drop-in biofuel, which is compliant with EN590 norms in a sustainable manner. In this project, a holistic fuel characterization is planned to assess the fuel characteristics and engine performance of this new paraffinic biofuel, consisting of about 30 vol% bio-alcohols.
This deliverable report summarizes the drop-in potential of REDIFUEL fuel investigated on a heavy-duty demonstrator long-haul truck. The utilization of either pure REDIFUEL or its mixture in diesel enables a good engine performance with well operation exhaust aftertreatment leading a similar fuel consumption and NOX emission level. Further, it behaves beneficial on significant lower particulate emissions.

Contents

1 Introduction

This deliverable report is part task 3.10 “Report on emission impact on existing vehicles and the fleet under real driving conditions” of the work package 3 “Biofuel-fuel system compatibility aspects and engine related evaluation” within the REDIFUEL project. The objective is to transfer the findings of the fuel screenings at the single cylinder into a multi-cylinder engine operation under real driving condition on a heavy-duty demonstrator vehicle and further to demonstrate the drop-in capability of REDIFUEL fuel.

Two different fuel candidates 40 vol% of RFA_{30P70} in diesel and 100 vol% of RFA_{30P70} have been tested and evaluated on their engine performance behaviour with respect to fuel consumption and emission output. The results are further emphasizing the potential of REDIFUEL as a promising renewable fuel blend candidate.

2 Methods

2.1 DEMONSTRATOR VEHICLE SETUP

The heavy-duty vehicle used for the real driving tests in the REDIFUEL project is a N3 Daimler Actros 1845 LS 4x2 tractor equipped with a 12.8 l engine with high pressure EGR and homologated to Euro VI-C. The rated power of the engine is 335 kW at an engine speed of 1600 min^{-1} and the type approval reference work [1] in the WHTC is 29.4 kWh. Figure 1 shows the demonstrator vehicle together with a standard trailer.

Figure 1 HD demonstrator vehicle

The engine is prepared with required sensors to measure temperature and pressure continuously and independent to the engine operation. Further, an advanced exhaust aftertreatment system (EATS) is also installed for research purpose. A schematic representation of the EATS can be seen in Figure 2.

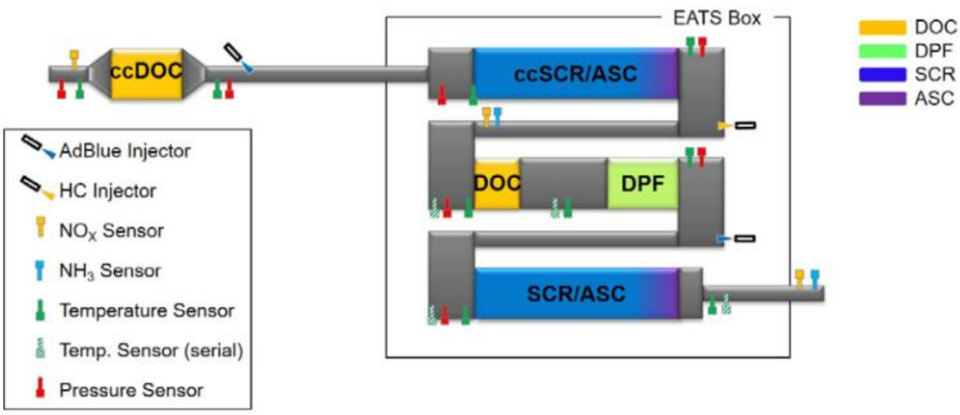

Figure 2 Layout and instrumentation plan of the emission control system

To assure full system understanding, the EATS is fitted with sensors as well as several injectors. NO_X sensors are fitted downstream of the turbine, downstream of the first SCR system and at the tailpipe to allow for full system measurement and full system control.
These sensors deliver a necessary input for the control of each of the SCR systems individually. NH_3 sensors are installed downstream of both SCR systems to monitor the ammonia slip from each individual SCR and to assist in the calibration of both systems. Temperature sensors are fitted upstream and downstream of all the EATS components as well as between the SCR substrates for in catalyst temperature monitoring.
Pressure sensors are also placed throughout the system for backpressure determination and comparative analysis to check for potential blockages from HC/soot or urea. The OEM delta pressure sensors are fitted upstream and downstream of the diesel particulate filter (DPF) for regeneration control and monitoring.

An enhanced Portable Emissions Measurement System (PEMS) is installed at engine tailpipe to the demonstrator vehicle as shown in Figure 3 below. This allows to measure all regulated emissions during the test continuously. The tailpipe is further modified to contain the Exhaust Flow Meter (EFM) for the PEMS kit and the equipment itself is set up in the trailer bed.
The PEMS kit contained NO and NO_2 analysers to determine tailpipe NO_X speciation, as well as CO and CO_2 measurement devices. In addition to the gaseous measurements, PN_{10} measurement equipment is also fitted. NO is measured using chemiluminescence spectroscopy. NO_2 is measured using photo acoustic sensor technology. CO and CO_2 are measured using nondispersive infrared spectroscopy (NDIR) and the PN is measured using a condensing particle counter (CPC).
In addition to the standard equipment, the truck is additionally fitted with both NH_3 and N_2O measurement technology. N_2O is measured using a portable Interband Cascade Laser and the NH_3 is measured using a portable Quantum Cascade Laser setup.

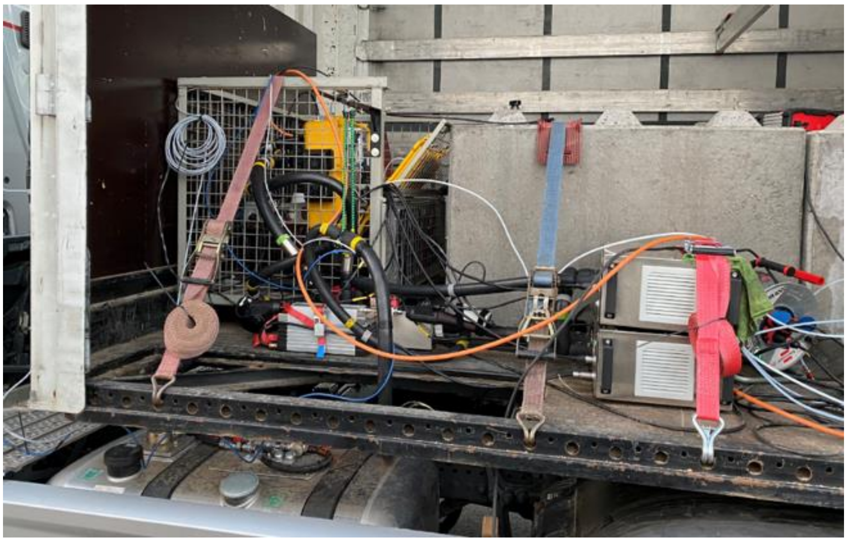

Figure 3 PEMS installation in the vehicle trailer bed

2.2 EMISSION CONTROL TECHNOLOGY SYSTEM

As shown in Figure 2, a close-coupled Diesel Oxidation Catalyst (ccDOC) is fitted directly behind the turbine for fast CO and HC control and to allow optimal heat transfer into the emissions control system. The outlet cone of the DOC is modified to integrate an urea injector, allowing the use of the downpipe and compensator for optimal mixing of the injected AdBlue® before entering the close-coupled Selective Catalytic Reduction (ccSCR) catalyst. The ccSCR has a

zone coated Ammonia Slip Catalyst (ASC) to ensure minimized secondary emissions creation. This close-coupled system has been integrated with the purpose of improving the cold-start, low temperature and city driving emission performance.
Downstream of the ccSCR system, the system layout resembles that of a conventional truck emission control system design, containing a DOC and catalysed DPF with integrated Hydrocarbon (HC) doser for DPF regeneration support. Downstream of the DPF is a second urea injector and mixing pipe before the second SCR with an integrated ASC to minimize ammonia slip.
A novel twin dosing system is 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 optimize conversion efficiency. As an example, it determines, based on the colder temperatures of cold-start operation that the conversion should be dominated by the first system. Further details on the system can be found in [2, 3].

2.3 DRIVING CONDITIONS

The driving conditions covered by the tests chosen to be representative of a realistic variation of heavy-duty vehicle types, with a special focus on long-haul operations. This in-service conformity (ISC) route containing urban, rural and motorway driving shares. An exemplary ISC route is represented in **Figure 4**.

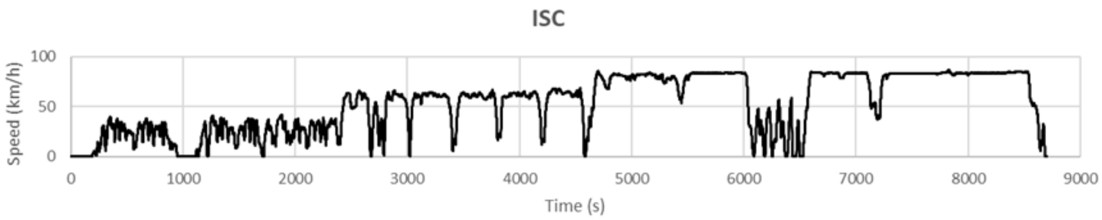

Figure 4 ISC driving route (exemplary)

The route ensures a broad coverage of the engine operating map including full load operation, seen in **Figure 5**.

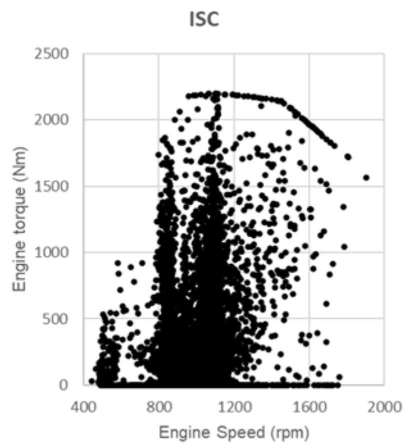

Figure 5 Engine operation range of ISC (exemplary)

2.4 INESTIGATED FUELS

Table 1 shows the relevant fuel properties of the investigated fuels and blend that have been tested on the demonstrator vehicle, as the CN and oxygen content increase, the carbon content and the calorific value decrease with RF_{A30P70} in diesel.

Table 1 Fuel properties of selected blends

Fuel	Density at 15 °C / kg/m³	Carbon mass fraction / %	Hydrogen mass fraction / %	Oxygen mass fraction / %	Calorific value / MJ/kg	Cetane number / 1
100 % B0 diesel	839.0	86.5	13.8	0.0	42.9	52.1
60 % B0 + 40 % RF_{A30P70}	820.3	84.42	14.26	1.47	42.5	53.6
100 % RF_{A30P70}	787.7	81.3	14.94	3.67	41.79	56.9

3 Results

The vehicle investigations have been operated considering almost the same route. To comply with real driving ISC requirements it was necessary to adapt the test routing in some cases, due to road closes (e.g. accident or construction works) on urban and rural sections or very slow traffic (e.g. traffic jam on the motorway). Therefore, the vehicle speed profile as well as the conducted work of engine requirement over time are slightly different between the investigated tests, see Figure 6.

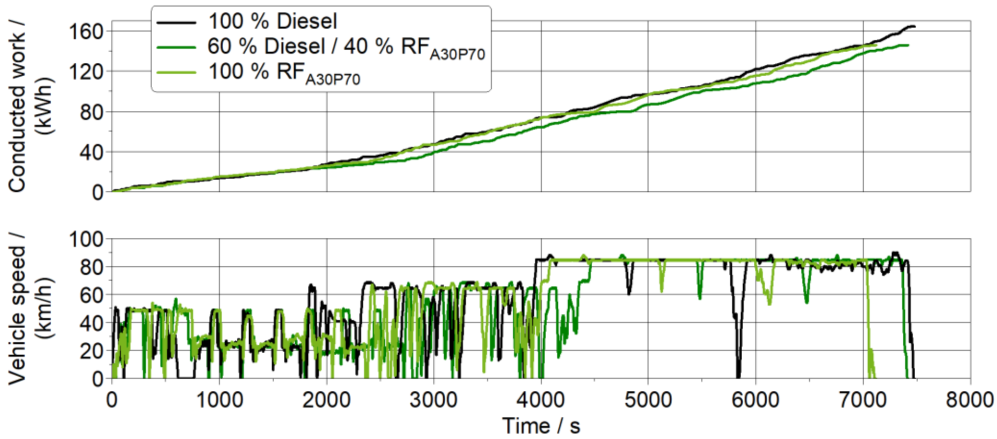

Figure 6 Conducted work of the engine and corresponding vehicle speed over time measured for diesel, 60 vol% diesel / 40 vol% RF$_{A30P70}$ blend and 100 vol% RF$_{A30P70}$

In the following, results are evaluated over conducted engine work to ensure a scientific analysis and valid assessment of the measurements.

The fuel consumption (FC) over conducted work measured on at the demo truck is shown in Figure 7. In general, the FC is higher during the urban driving conditions (conducted work <30 kWh). This is due to the overall lower efficiency of part load operation. The rural fuel consumption (conducted work 30-60 kWh) is lower than the motorway equivalent (conducted work >60 kWh), this is caused by the more transient operation nature of the truck during the motorway section. Further, the FC measurements show that either the blend 40 vol% RF$_{A30P70}$ in diesel or the pure REDIFUEL fuel of 100 vol% of RF$_{A30P70}$ remain at a similar overall level compared to pure diesel. It approves the good drop-in capability of REDIFUEL without any engine calibration adaptation.

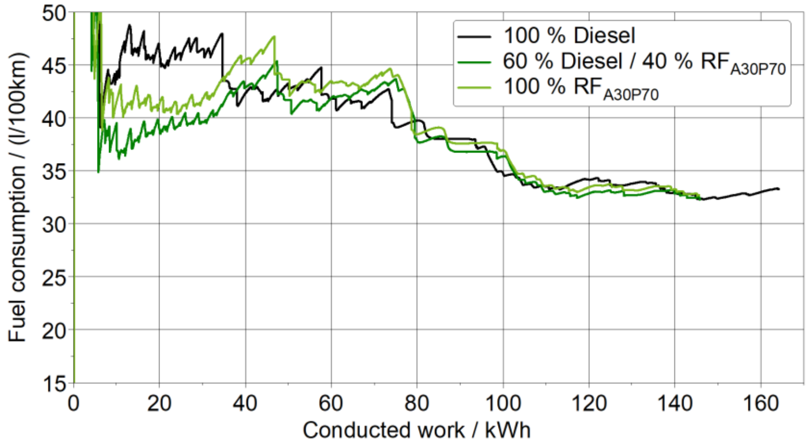

Figure 7 Fuel consumption over conducted work measured for diesel, 60 vol% diesel / 40 vol% RF_{A30P70} blend and 100 vol% RF_{A30P70}

The NO_X engine-out emissions show the same tendency as FC shown before. The demo vehicle engine is calibrated to an average of around 5 g/kWh NO_X engine-out representing a common EU VI-C level. The results measured for diesel is shown in Figure 8. Additionally, the specific NO_X engine-out emission remain on a same level when dropping-in REDIFUEL into diesel. The result of 40 vol% RF_{A30P70} in diesel as well as 100 vol% of RF_{A30P70} show some slightly increased NO_X emissions when entering the rural section of the ISC route. That change does not affect the overall emission results. The NO_X emission end up on a very similar level by the end of the test.

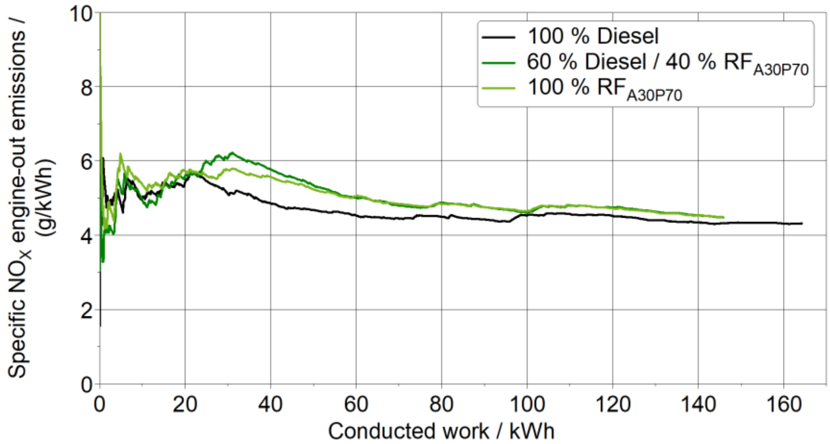

Figure 8 Specific NO_X engine-out emissions over conducted work measured for diesel, 60 vol% diesel / 40 vol% RF_{A30P70} blend and 100 vol% RF_{A30P70}

The fuel screening of different REDIFUEL mixtures at the single cylinder have demonstrated the excellent soot reduction potential due to the fuel specification of paraffinic and alcohols, see REDIFUEL deliverable D3.7. Since the demo vehicle is equipped with a PEMS only particulate numbers at tailpipe have been measured. It must be mentioned that the used PEMS is able to measure PN10. Of course, this represents expected PN size for upcoming emission legislation and provides more sophisticated results compared with current emission legislation.
The comparison of PN_{10} (counting of particulate size > 10 nm) of diesel combustion against 40 vol% RF_{A30P70} in diesel is shown in Figure 10. It shows that the fuel blend 40 vol% RF_{A30P70} in diesel leads to a high number of particulates during low load operation under urban condition. It is assumed that the paraffinic content of the REDIFUEL provides more particulate emissions in the size range below 20 nm in this engine operation range. Pravesh Chandra Shukla et al. [5]

have investigated particulate size distribution of diesel and HVO at different operating conditions. Figure 9 summarizes the results of the distribution measurement. HVO tends to higher PN emission below 20 nm at low engine loads of up to 10 bar of BEMP in combination with high injection rail pressure in the range of 1500-2000 bar.

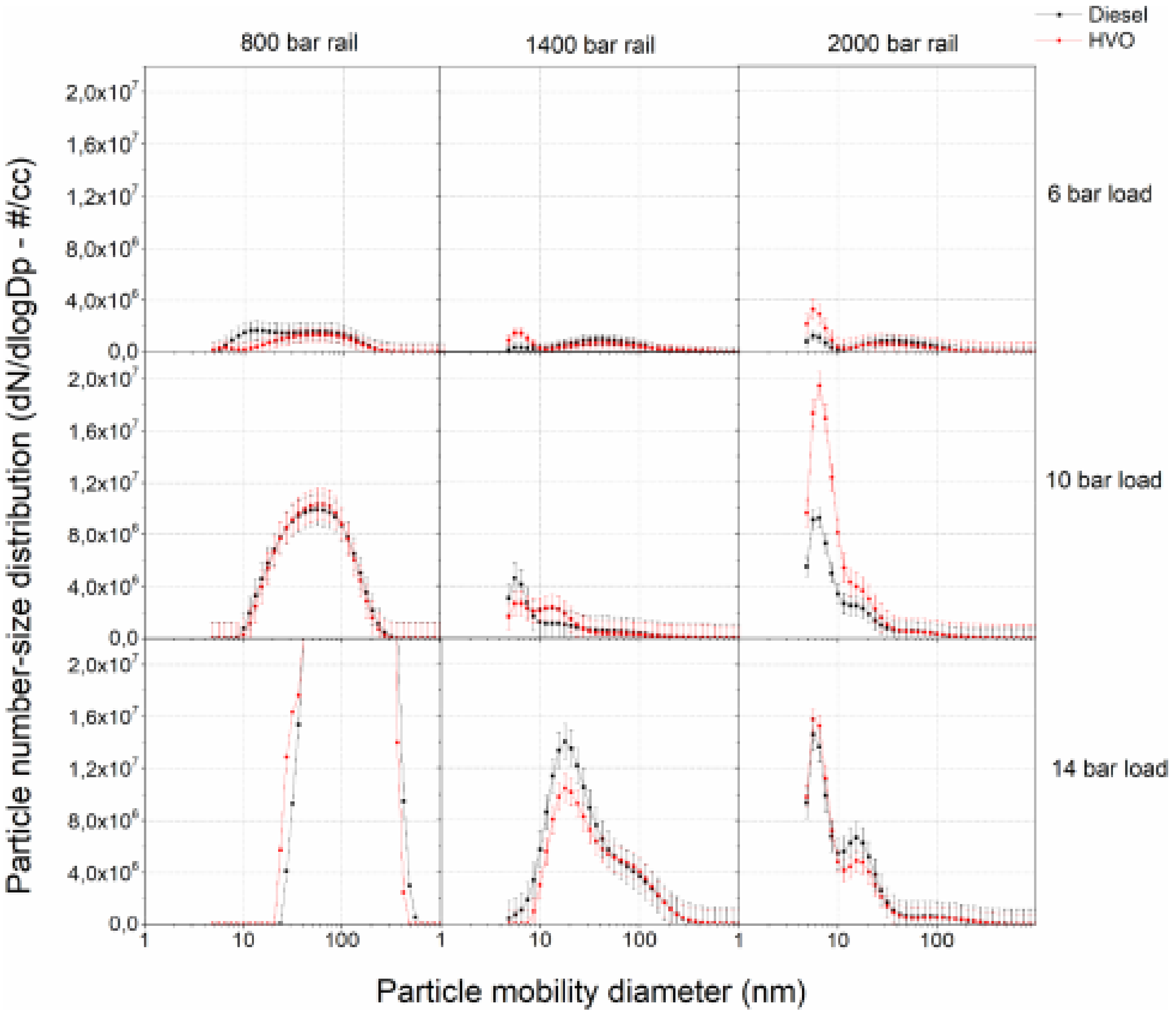

Figure 9 Particle number size distribution for diesel and HVO [5]

Modern HD engines already operate with an injection rail pressure >1200 bar at low part load that can lead to increased PN emission by paraffinic diesel. The literature provides only little information about the mentioned phenomenon yet. Since PN_{10} will become important for future emission legislation further investigations with respect to paraffinic diesel has to be considered. The analysis of particulate size distribution of paraffinic diesel will also be part of the EU funded research project LONGRUN. The results should give further insights into this phenomenon. Additionally, the low PN-size can lead to a lower growth of the soot cake on the particulate filter that usually supports the filtration function of the DPF. During medium load operation at rural section the particulate numbers are dropping significantly that enables an even lower level compared to diesel. The high load operation at motorway section provides a constant tendency between the two fuels as high combustion temperatures occurs where particulate emissions are low.

Nevertheless, the challenge of increased particulate emissions at low loads does not lower the great potential of REDIFUEL. OEM and TIER1 supplier are already working on suitable countermeasures and technical solutions for elimination, ref. [6, 7].

The test of 100 vol% RF_{A30P70} has shown some issue with the particulate emission measurement and are not represented in Figure 10.

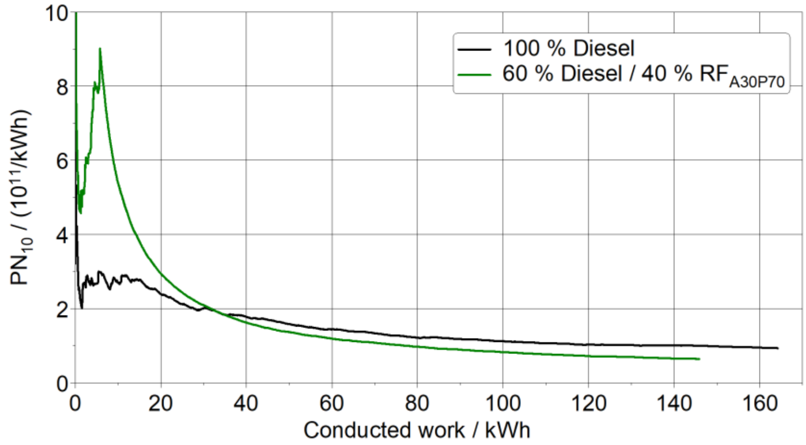

Figure 10 Particulate number over conducted work measured for diesel and 60 vol% diesel / 40 vol% RF_{A30P70} blend

4 Discussion and Conclusions

4.1 4.1 DISCUSSION

No decisions are made based on the described results, that have provided a deviation from the grand agreement.

4.2 4.2 CONCLUSIONS

The presented results achieved within the obtained investigation on FEVs HD demonstrator truck have verified the previous findings from the single cylinder fuel screenings. The vehicle results of the ISC PEMS test have demonstrated the great potential with a share of 40 vol% RF_{A30P70} in diesel. That EN590-compliant fuel blend operates very similar in terms of emission behaviour and drivability to conventional diesel fuel. Both NO_X and total CO_2 tailpipe emissions act on the same level, summarized in Figure 11. In fact, RF_{A30P70} sources on fully renewable energy and carbon the Well-to-Wheel CO_2 footprint can be reduced significantly. Those results validate the key findings from the single cylinder fuel screening camping.

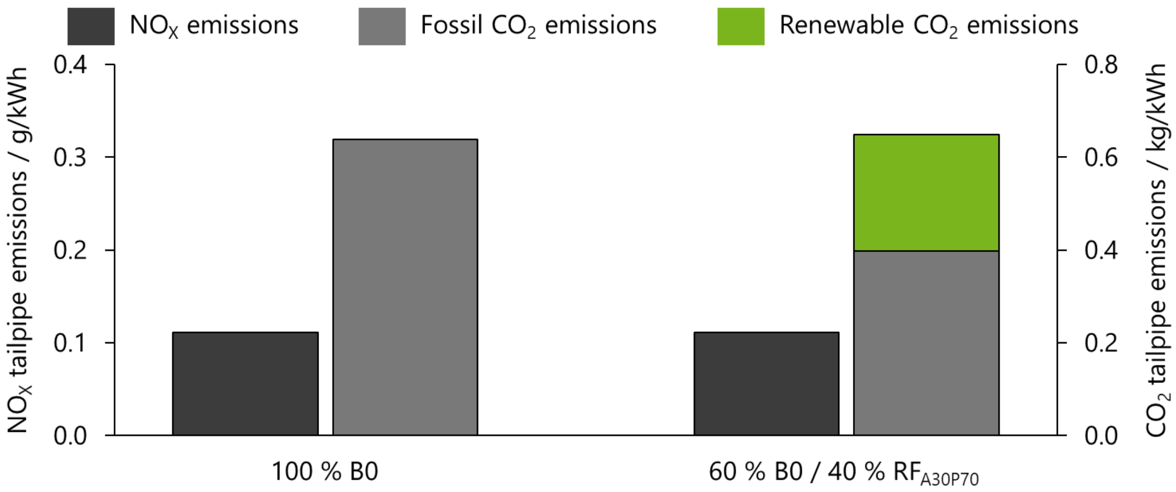

Figure 11 NO_X and CO_2 Tailpipe emissions results for fuel blend of 60 vol% B0 diesel / 40 vol% RF_{A30P70} compared against pure diesel out of ISC PEMS test at a HD demonstrator vehicle

In general, RF_{A30P70} has proven as a great successor for future renewable fuel candidates, either as pure fuel or mixed with diesel as EN590-compliant. Even if total CO_2 tailpipe emissions remain similar compared to conventional diesel it still behaves beneficial on the Well-to-Wheel CO_2 emissions significantly.

5 Deviations from Annex 1

There are no deviations with respect to the description of work.

6 References

[1] 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.

[2] Mendoza Villafuerte, P., Demuynck, J., Bosteels, D., Wilkes, T., Robb, L., Schönen, M.; Demonstration of Extremely Low NOx Emissions with Partly Close-Coupled Emission Control on a Heavy-Duty Truck Application, 42nd International Vienna Motor Symposium, 2021.

[3] Mendoza Villafuerte, P., Demuynck, J., Bosteels, D., Wilkes, T., Recker, P.; Ultra-Low NOx Emissions with a Close-Coupled Emission Control System on a Heavy-duty Truck Application, SAE Powertrains, Fuels & Lubricants Meeting, 2021.

[4] Mendoza Villafuerte, P., Demuynck, J., Bosteels, D., Gioria, R., Selleri, T., Melas, A., Suarez-Bertoa, R., Perujo, A., Wilkes, T., Robb, L., Recker, P.; Ultra-Low NOx Emissions with a Close-Coupled Emission Control System on a Heavy-duty Truck Application, 30th Aachen Colloquium Sustainable Mobility, 2021.

[5] Pravesh Chandra Shukla, Sam Shamun, Louise Gren, Vilhelm Malmborg, Joakim Pagels, Martin Tuner; Investigation of Particle Number Emission Characteristics in a Heavy-Duty Compression Ignition Engine Fueled with Hydrotreated Vegetable Oil (HVO), SAE International Journal of Fuels and Lubricants , Vol. 11, No. 4 (2018), pp. 495-506.

[6] Viswanathan, S., George, S., Govindareddy, M., and Heibel, A., "Advanced Diesel Particulate Filter Technologies for Next Generation Exhaust Aftertreatment Systems", SAE Technical Paper 2020-01-1434, 2020.

[7] BASF press release, “Diesel Particulate Filters - Diesel emissions control solutions“, BASF-8453 06/19, 2019.

7 Acknowledgement

H2020-LC-SC3-RES-21-2018-DEVELOPMENT OF NEXT GENERATION BIOFUELS AND ALTERNATIVE RENEWABLE FUEL TECHNOLOGIES FOR ROAD TRANSPORT

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8 Risk register

Risk No.	WP	What is the risk?	Probability of risk occurrence[1]	Effect of risk[2]	Solutions to overcome the risk
1	3.4	Possible engine damage (rebuild / repair not possible in time)	2	1	Procurement of spare parts, spare cylinder head; definition of engine shut-down limitations
2	3.4	Lead time of ordered components too long	2	2	Regular (monthly) alignment of delivery time plan with suppliers

[1] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

[2] Effect when risk occurs: 1 = high, 2 = medium, 3 = Low