Deliverable report

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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 single cylinder research engine. Introduction of new (biogenic) fuels into the market is most likely to happen by blending into the existing improved infrastructure. Overall, it was observed that the utilization of REDIFUEL blended in diesel enables slightly improved engine efficiency while simultaneously reducing pollutant emissions. The extend of the improvements increase with increasing REDIFUEL share in the fuel.

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1 Introduction

This deliverable report is part task 3.6 “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 initial objective has been to evaluate the impact of an advanced engine control on efficiency and performance by directly accounting for the fuel’s properties, i.e. alcohol content. However, during the course of the project it became obvious, that the overall alcohol content of the REDIFUEL product will not be varied, but is rather fixed at about 30% v/v. The main reason for is that one of the project’s objective has been to synthesize an EN590 compatible fuel. For this reason, high shares of alcohols in the fuel have been required, otherwise the product would have fallen below the lower density limit of 800 kg/m³. At the same time, a share of ~30% v/v alcohol content in REDIFUEL displays the practical and economical limit. That is why REDIFUEL was investigated with 70% v/v paraffins and 30% v/v alcohols (RF_{A30P70}) throughout the course of the project.

Another reason for not differentiating between different alcohol content in the fuel is the limited availability of sensors that are able to properly detect long-chain alcohols. State-of-the art alcohol sensor determine the capacity changes and electric conductivity of the fuel; however, this working principle is valid for mainly short-chain alcohols like methanol and ethanol. At the time of the project no affordable, close to series production sensor for long-chain alcohols has been available.

Finally, it was observed that the impact of changes on fuel properties on engine performance and emissions is not as significant as expected (see also Deliverable 3.1 Report on spray and combustion behavior on new alcohol blended fuels). Other studies have revealed that higher shares of alcohol can significantly improve particulate matter emissions [1,2]. However, within this project such an enormous potential could not be explored, what is attributed mainly to the change in application. Whereas many studies have focused on passenger car applications, in REDIFUEL the emphasis has been on long-haul heavy duty trucking. A major difference is in the bore diameter and engine speed. The larger diameter enables longer spray and lift-off lengths, allowing for more air entrainment into the mixture. The lower engine speed provides more time for fuel and air mixing. Hence, the influence of the fuel itself on combustion performance and emissions is reduced compared to passenger car applications.

For this reason, the economic rational of adapting an engine control on different alcohol content in the fuel is not given for a truck and engine manufacturer.

Hence, within this deliverable different blends of REDIFUEL RF_{A30P70} with diesel have been evaluated with respect on engine performance and emissions in existing engines with series calibration at different engine-out NO_x levels.

2 Methods

To be drop-in capable by mixing with diesel a fuel must satisfy the EN590 standard. In the norm, several properties are regulated, such as oxidation stability, viscosity, boiling range, etc.. The research results of this deliverable, mainly two properties were considered: density and Cetane Number (CN). While the density is an indicator of the volumetric energy content of the fuel, ensuring a similar CN as diesel guarantees not major modifications to engine calibration and hardware. The diesel used in this research is a standard B0 diesel without biofuel content. Different blends of a surrogate alcohol mixture (SAM) with GtL and of the RF_{A30P70} (i.e., the surrogate mixture featuring a similar composition of the real end-product) with diesel are screened with regards to their self-ignition tendency and density. This preliminary screening served to identify a drop-in blend compliant with the EN590 regulation. Successively, blends of RF_{A30P70} with diesel were tested in a heavy-duty single cylinder engine (HD SCE), to assess the potential of efficiency gain and emissions reduction.

The results displayed within Section 3 show also indicated the systematic error by bar graphs. This systematic error was calculated from the reference points with diesel to assess the repeatability the SCE facility. The random error is computed as standard deviation from the single measures when averaged over the recording time on the test bench. Two errors summed via propagation (sum or root square). This tell us that the deviation in efficiency are within the measurement accuracy but that we can surely see a clear trend. If the efficiency change would be above 2% (relative) we can surely confirm a significant change. However, this analysis is very conservative if you remove the systematic error, calculated by the diesel measurements of reference point the changes in efficiency becomes significant.

2.1 HEAVY DUTY SINGLE CYLINDER ENGINE

The HD SCE was derived from a six-cylinder heavy duty commercial vehicle engine of N3 class compliant to Euro VI stage C. The engine specifications are listed in

Table 1. The engine featured a common rail fuel injector with a built-in pressure intensifier and an in-house developed prototype electronic control unit with a model-based fuel path control. Such a prototype control system provides a wide range of flexibility especially in adjusting relative separation and energizing duration of main injection, pilot injection and pressure intensifier. The exhaust gas recirculation (EGR) rate is derived from the CO_2 concentration in the intake runner. The exhaust back pressure (p_{exh}) is regulated with two flow control butterfly valves: one valve for a faster control and the other for a finer control of p_{exh}. The regulated emissions are measured at the engine exhaust. The measurement line for the unburned hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxides (NO_X) is pre-heated to a temperature of 200 °C to avoid condensation. The measurement devices used are listed in Table 2.

Table 1: HD SCE specifications

Parameter	Unit	Value
Displacement	liters	2.13
Stroke	mm	156
Bore	mm	132
Compression ratio	-	18.3
Max. cylinder pressure	bar	250
Max. injection pressure	bar	2700
Max. rail pressure	bar	1200
EGR	-	Cooled high pressure EGR
Injection system	-	CRIN 4.2 Bosch
Injection nozzle	cm^3/30s @ 100 bar	850
Number of holes	-	8
Injection nozzle cone angle	°	142

Table 2: Measuring devices for the HD SCE

Parameter	Device	Range
CO, CO2, NO_x, HC	FEVER NDIR, CLD, FID	CO ~ 0 – 5000 ppm CO2 ~ 0 – 20 %-vol NO / NO_X ~ 0 – 3000 ppm THC ~ 0 – 3000 ppm C3
Filter Smoke Number (FSN)	AVL 415S	0 – 10 FSN
Fuel flow	Emerson CMF010 Coriolis	0 – 120 kg/h
Combustion pressure sensor	Kistler 6044 A	0 – 300 bar

The combustion and emission behaviour of the fuels under consideration are assessed by testing these fuels at a given load for different EGR rates. Among that four load points have been selected ranging from low part loads up to rated power operation, see Figure 1. Furthermore, the selected load points are preferred because those are relevant for both the world harmonized stationary cycle (WHSC) and world harmonized transient cycle (WHTC) for emission regulation, see Figure 1. At engine part load, the in-cylinder thermodynamic conditions like temperature, pressure and turbulence are expected to be high enough to permit the assessment of the ignition behaviour of the fuels based on engine operation.

The given fuels are analysed at a Euro VI stage C base indicated specific nitrogen oxides ($ISNO_X$) level of around 6 g/kWh. While performing the EGR sweeps, a constant centre of combustion (α_{Q50}) is kept in order to avoid impact on emission of retarded combustion. The fuels are compared at the same engine indicated mean effective pressure (IMEP) as shown in Figure 1 and the relevant engine calibration parameters like, injection pressure (p_{inj}), boost pressure (p_{boost}) and temperature (T_{boost}) defined in Table 3.

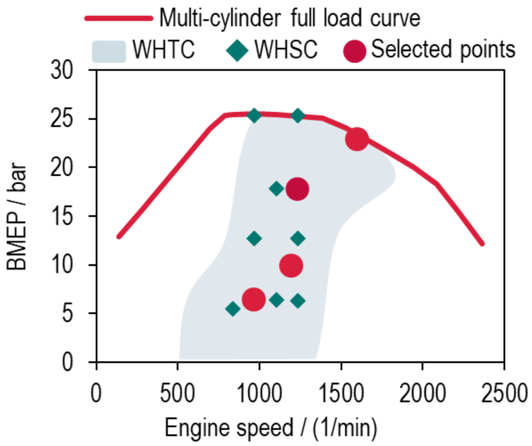

Figure 1: Explicative engine load map in break mean effective pressure (BMEP) vs engine speed

Table 3: HD SCE calibration settings

Engine speed / min^{-1}	BMEP/ bar	IMEP / bar	α_{Q50} / °CA ATDC	p_{inj} / bar	T_{boost} / °C	p_{boost} / mbar	p_{exh} / mbar
1600	22.8	24.9	15.1	2612	54	3500	3623
1200	19.6	21.0	10.2	1680	39	2800	2904
1200	9.8	10.3	6.2	1280	41	1790	1825
900	5.9	6.4	6.5	1037	41	1280	1325

In Table 4, the relevant fuel properties of the blends that are tested on the HD SCE are mentioned, as the CN and oxygen content increase, the carbon content and the calorific value decrease with an increase in the RF_{A30P70} share. Besides that, the fully renewable fuel blend of 93 vol% RF_{A30P70} and 7 vol% UCOME is investigated.

Table 4: Fuel blend properties

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
80 % B0 + 20 % RF_{A30P70}	829.8	85.46	14.03	0.74	42.7	52.5
60 % B0 + 40 % RF_{A30P70}	820.3	84.42	14.26	1.47	42.5	53.6
50 % B0 + 50 % RF_{A30P70}	815.2	83.90	14.37	1.82	42.3	54.1
20 % B0 + 80 % RF_{A30P70}	798.9	82.34	14.71	1.83	42.0	56.7
93 % RF_{A30P70} + 7 % UCOME	800.2	81.01	14.74	4.17	41.4	57.9

3 Results

In the following section, the results from the screening of the fuel blends on the HD SCE are discussed. The presented results are obtained at an engine speed of 1200 min^{-1} and two different NO_x-levels: 5.8 g/kWh and 3.0 g/kWh. This was done to also explore the impact of possible future emission legislation.

Cruise point

In Figure 2, the results for the cruise point operation at the base $ISNO_X$ of 5.8 g/kWh are presented. The different fuel blends are displayed in bar charts and distinguished by colour style. The indicated specific particulate matter emissions (ISPM) are presented in the top-left plot in Figure 2. Generally, adding the RF_{A30P70} to diesel reduces the ISPM emission.

This can be attributed to the presence of oxygen and paraffinic molecules in the RF_{A30P70}. Less soot precursors are generally formed when diluting diesel with a straight-chained oxygenated mixture, as shown in the literature [8, 9]. Moreover, this renewable drop-in fuel might positively affect also soot oxidation, due to its fast ignition chemistry and enhanced mixture formation properties [9]. As the 40 vol% RF_{A30P70} in diesel is compliant with EN590 in accordance with previous discussions, in this result section the relative changes with reference to diesel in performance and emissions are presented for this blend only. A relative reduction of ISPM by up to 12 % is achieved with a blending proportion of 40 vol% RF_{A30P70} in diesel.

The indicated specific carbon monoxide (ISCO) emissions are shown in the middle-left corner of Figure 2. With an increase in RF_{A30P70} substitution in diesel, lower ISCO emissions are observed. This could be attributed to the faster ignition, which would prevent over-leaning in air/fuel mixture and to the inherent oxygen moieties included in the renewable fuel. Moreover, an enhanced mixture formation (due to better atomization owing to the paraffinic content) is also beneficial to ensure a proper oxygen entrainment [10]. The indicated specific hydrocarbon (ISHC) emissions, shown in the lower-left bar plot in Figure 2, reduce with increasing RF_{A30P70} share. Similarly to ISCO emissions, an improved mixture formation might be the reason for the observed trend [10]. Due to reduced ISCO and ISHC emissions, a marginal rise in the indicated thermal efficiency (ITE) by 0.6 %-points was noticed for the blend with 40 vol% RF_{A30P70} in diesel, as shown in top-right diagram of Figure 2. A relative reduction in ISCO and ISHC by up to 6 % and 18 % is respectively noticed for the blend under consideration.

Generally, an increase in RF_{A30P70} share leads to a direct reduction in indicated specific carbon dioxide ($ISCO_2$) emissions. A relative reduction in $ISCO_2$ by up to 2.6 % is seen for the blend with 40 vol% RF_{A30P70} in diesel, refer middle-right diagram of Figure 2. To explain this $ISCO_2$ reduction, a parameter named as theoretical fuel carbon flow rate (TFCFR) is introduced. The TFCFR is defined as the fuel carbon mass fraction times the fuel mass flow rate. It represents the theoretical carbon mass flow rate that is available for a complete combustion of the fuel at a given engine load, accounting for variations in injected fuel mass due to changes in calorific fuel content and ITE. The lower-right corner of Figure 2 shows a TFCFR reduction by 2.3 % for the blend with 40 vol% RF_{A30P70} in diesel, which nearly agrees with the aforementioned relative $ISCO_2$ reduction.

In addition to that, the blend with 93 vol% RF_{A30P70} and 7 vol% UCOME provides some further potential due to its high content of paraffinic hydrocarbons and increased share of molecular oxygen. Both lead to an improved mixture formation and fasten combustion. The results show a relative reduction in ISCO and ISHC by more than 20 % and 32 % while ISPM emission are lowered by around 15 %.

The improved mixture formation and fasten combustion result in a better combustion efficiency and show a ITE rise by around 0.9 %-points. The TFCTR is reduced by more than 5 %.

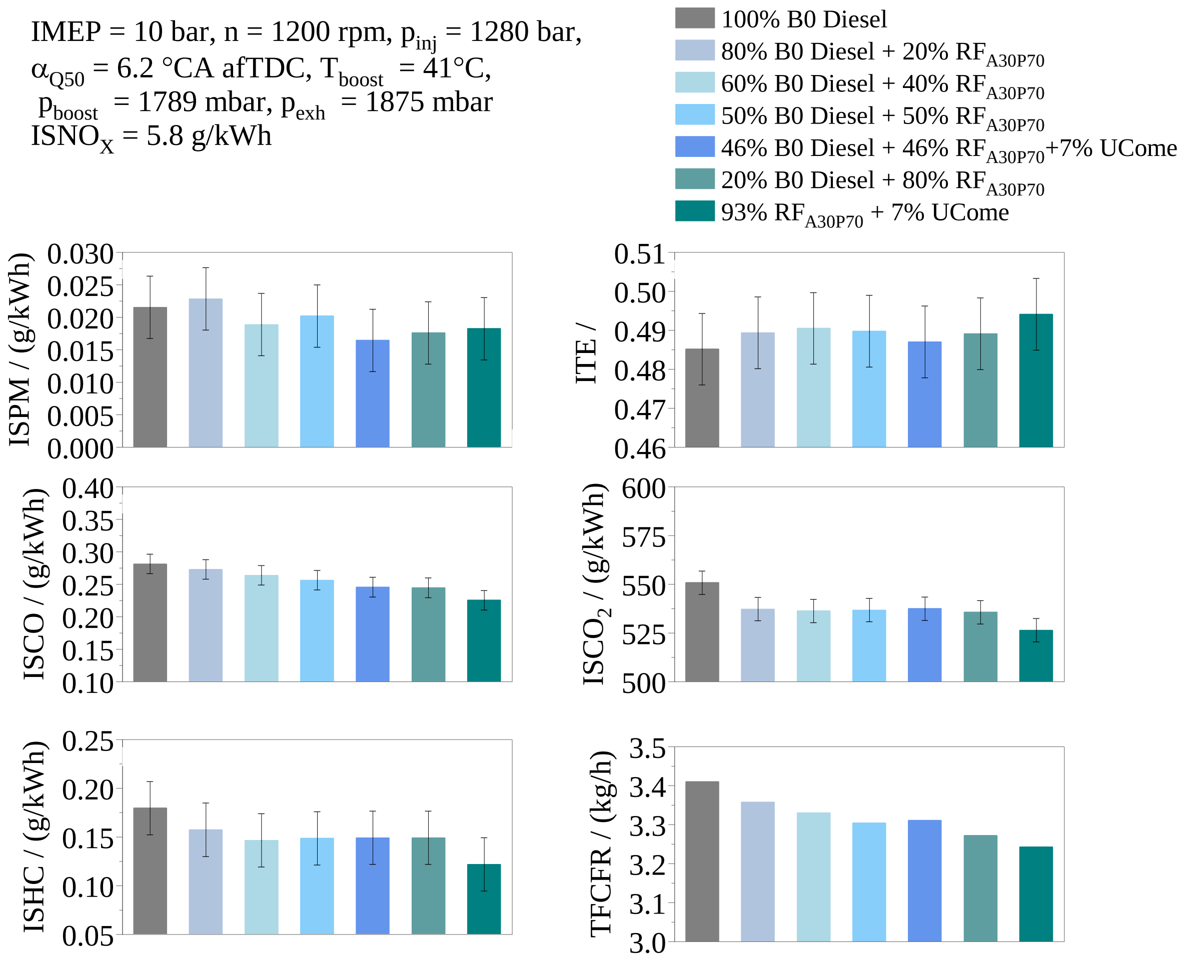

Figure 2: HD SCE results at cruise point for base NOx level, IMEP = 10 bar, n = 1200 min^{-1}, p_{inj} = 1280 bar, α_{Q50} = 6.2 °CA a. TDC, T_{boost} = 41 °C, p_{boost} = 1789 mbar, p_{exh} = 1875 mbar, $ISNO_X$ = 5.8 g/kWh

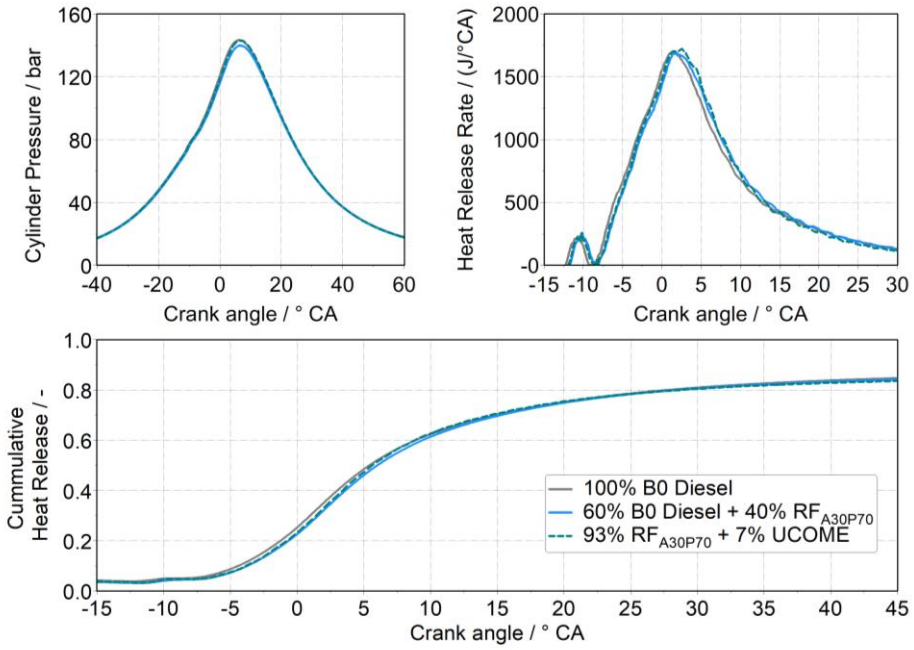

Figure 3 Heat release analysis at cruise point IMEP = 10 bar, n = 1200 min^{-1}, p_{inj} = 1280 bar, α_{Q50} = 6.2: °CA a. TDC, T_{boost} = 41 °C, p_{boost} = 1789 mbar, p_{exh} = 1875 mbar, $ISNO_X$ = 5.8 g/kWh

The heat release analysis for the cruise point at the base $ISNO_X$ level is shown in Figure 3. For the sake of clarity, the Figure 3 presents the heat release analysis for diesel and blends of RF_{A30P70} with 40 vol% / 60 vol% in diesel and the fully renewable blend of 93 vol% RF_{A30P70} / 7 vol% UCOME. Due to a slightly lower ignition delay time (i.e. slightly higher CN) of the RF_{A30P70} blends with diesel, the injection timing is slightly retarded to maintain a constant α_{Q50}. This can be seen in the cumulative heat release plot at a value of around 0.5, refer lower diagram of Figure 3. The heat release rate (HRR) of the RF_{A30P70} blends, depicted on the upper-right side in Figure 3, is similar to that of diesel. The crank angle position corresponding to the maximum heat released during combustion is slightly retarded for the RF_{A30P70} blends. This can be attributed to an increased injector energizing time - necessary to achieve the load matching (i.e. increased injected mass to compensate the reduced fuel calorific value) - and to the retarded injection timing. Increased injected fuel mass causes a relatively later end of combustion and a subsequent shift in heat release.

Figure 4 shows the analysis of the change in efficiency and losses with 100% fossil diesel, with RF_{A30P70} with 40 vol% / 60 vol% in diesel, and the fully renewable blend of 93 vol% RF_{A30P70} / 7 vol% UCOME. Due to slightly faster combustion of the renewable fuel, the exhaust gas enthalpy is reduced. However, the faster combustion unfortunately also causes higher heat losses to the combustion chamber walls. Hence, the overall gain in engine efficiency is limited.

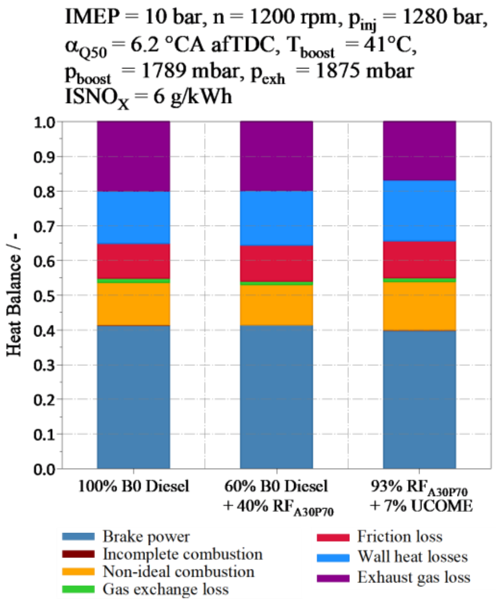

Figure 4: Share of losses IMEP = 10 bar, n = 1200 min^{-1}, p_{inj} = 1280 bar, α_{Q50} = 6.2 °CA a. TDC, T_{boost} = 41 °C, p_{boost} = 1789 mbar, p_{exh} = 1875 mbar, $ISNO_X$ = 5.8 g/kWh

In addition to the engine's serial calibration, also tests with reduced engine-out NO_x-levels have been performed. These investigations have been performed to explore the impact of both future emission legislations such as EU VII. The test results at Cruise Point with lower engine-out NO_x emissions are given in Figure 5.

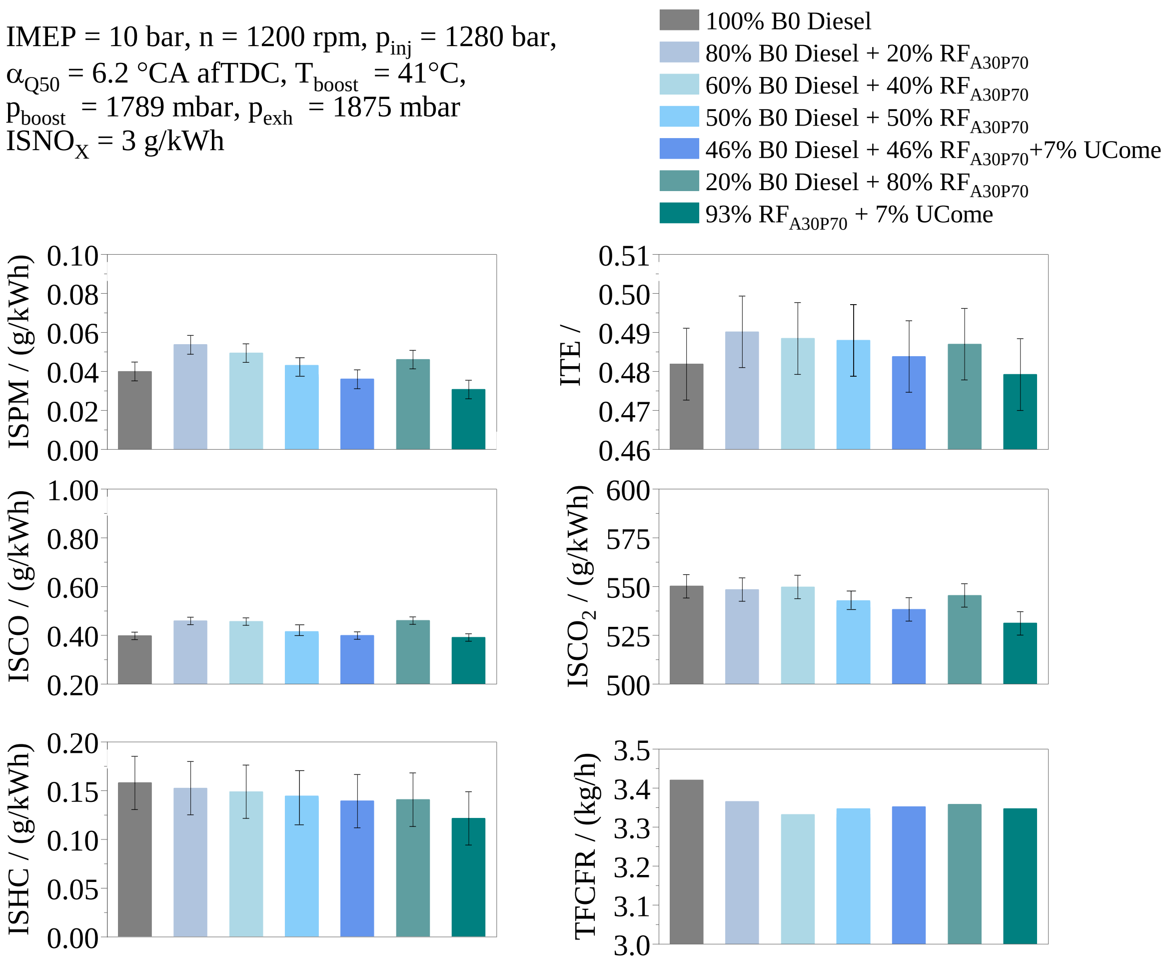

Figure 5: HD SCE results at cruise point for base NO$_X$ level, IMEP = 10 bar, n = 1200 min^{-1}, p_{inj} = 1280 bar, α_{Q50} = 6.2 °CA a. TDC, T_{boost} = 41 °C, p_{boost} = 1789 mbar, p_{exh} = 1875 mbar, ISNO$_X$ = 3.0 g/kWh

The overall trend in emissions and efficiency remain mainly unchanged when comparing to the results discussed in Figure 3 for higher NO$_x$-levels. Obviously, however, is a reduced indicated thermal efficiency at lower NO$_x$-levels what can be attributed to higher share of exhaust gas recirculation. This directly causes a change of the isentropic coefficient and also impacts combustion due to limited oxygen availability. But still, blends with REDIFUEL tend to show higher efficiencies than fossil diesel fuel.

Apart from that, also of course indicated specific hydrocarbons slightly decrease with increasing REDIFUEL share.

Best efficiency point

The results at the higher engine load point of best efficiency show in principle the same tendency, see Figure 6. It can be seen that blends of RF$_{A30P70}$ in diesel behave very similar to pure diesel with respect to their pollutant and CO$_2$ emission impact. The low emission potential of RF$_{A30P70}$ in diesel can be explained with the predominating high combustion temperature. Thus, excellent boundary conditions for an improved mixture formation and fast combustion are existed already for pure diesel.

The fully renewable blend of 93 vol% RF$_{A30P70}$ with 7 vol% UCOME provides overall improvements also at high load. The ISCO emissions are reduced by more than 20 % while the particulate emissions are lowered by more than 50 %. The ISHC emissions slightly increased of 30 %, but they remain on a significant low level. Again, the high content of paraffinic hydrocarbons and increased share of molecular oxygen are led to a fast combustion that improves the engine efficiency by around 1 %-point. The TFCTR has also been reduced in the manner of 4 %.

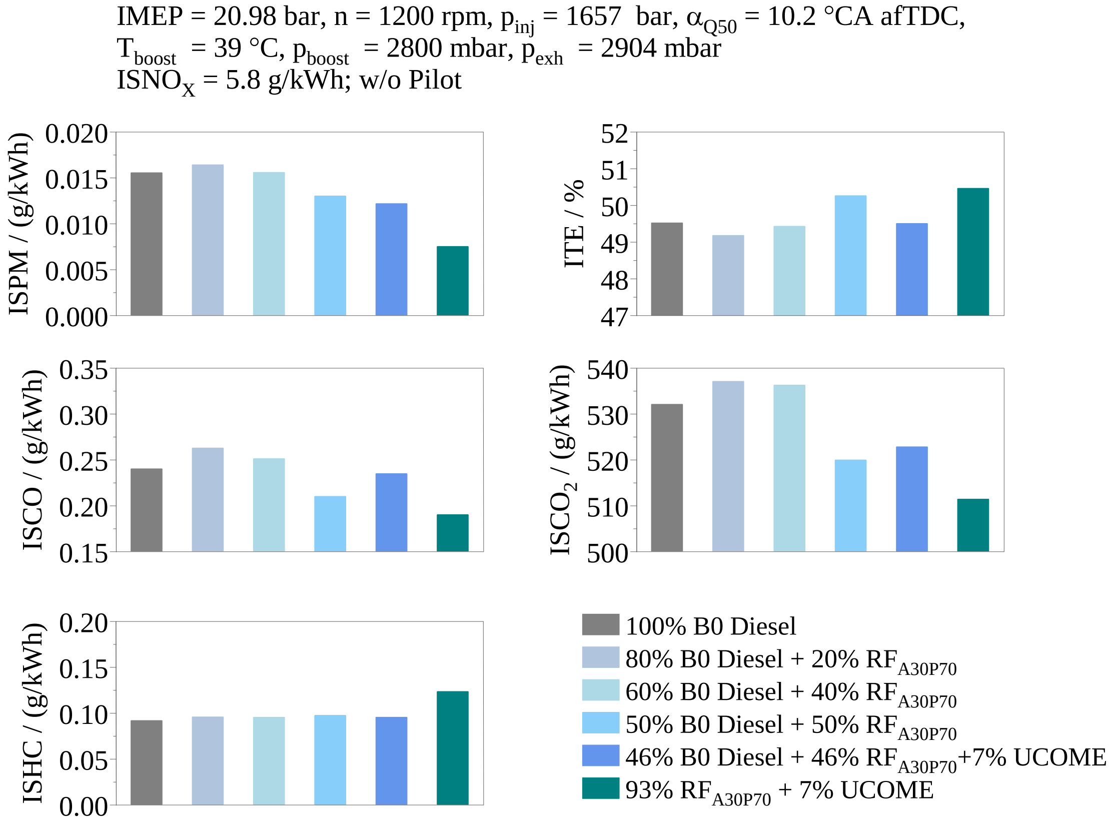

Figure 6: HD SCE results at best efficiency point for base NO$_X$ level, IMEP = 20.98 bar, n = 1200 min^{-1}, p_{inj} = 1658 bar, α_{Q50} = 10.2 °CA a. TDC, T_{boost} = 39 °C, p_{boost} = 2800 mbar, p_{exh} = 2904 mbar, ISNO$_X$ = 5.8 g/kWh

Figure 7 shows the results of the heat release rate analysis. As anticipated from the above shown results, the cumulated heat release of 40 vol% RF$_{A30P70}$ in diesel shows a similar combustion behaviour then pure diesel. Only 93 vol% RF$_{A30P70}$ with 7 vol% UCOME delivers an improved burn-out of the diffusive phase due its molecular oxygen content with the mentioned benefit in efficiency and emissions.

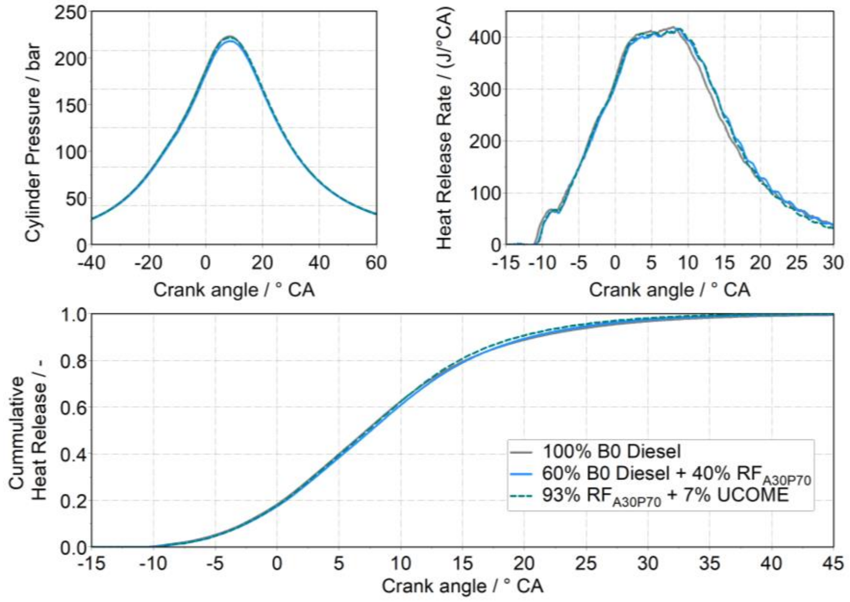

Figure 7: Heat release analysis at best efficiency point for base NO_X level, IMEP = 20.98 bar, n = 1200 min^{-1}, p_{inj} = 1658 bar, α_{Q50} = 10.2 °CA a. TDC, T_{boost} = 39 °C, p_{boost} = 2800 mbar, p_{exh} = 2904 mbar, $ISNO_X$ = 6.1 g/kWh

Also in the best efficiency point different NO_x-levels have been investigated, see Figure 8. As for the lower load point, the main statements remain unchanged. Also at lower NO_x-emission, a clear benefit in indicated specific particulate matter emissions and indicated efficiency. As in the Cruise Point, the higher EGR-share required for low NO_x at engine out also reduces efficiency.

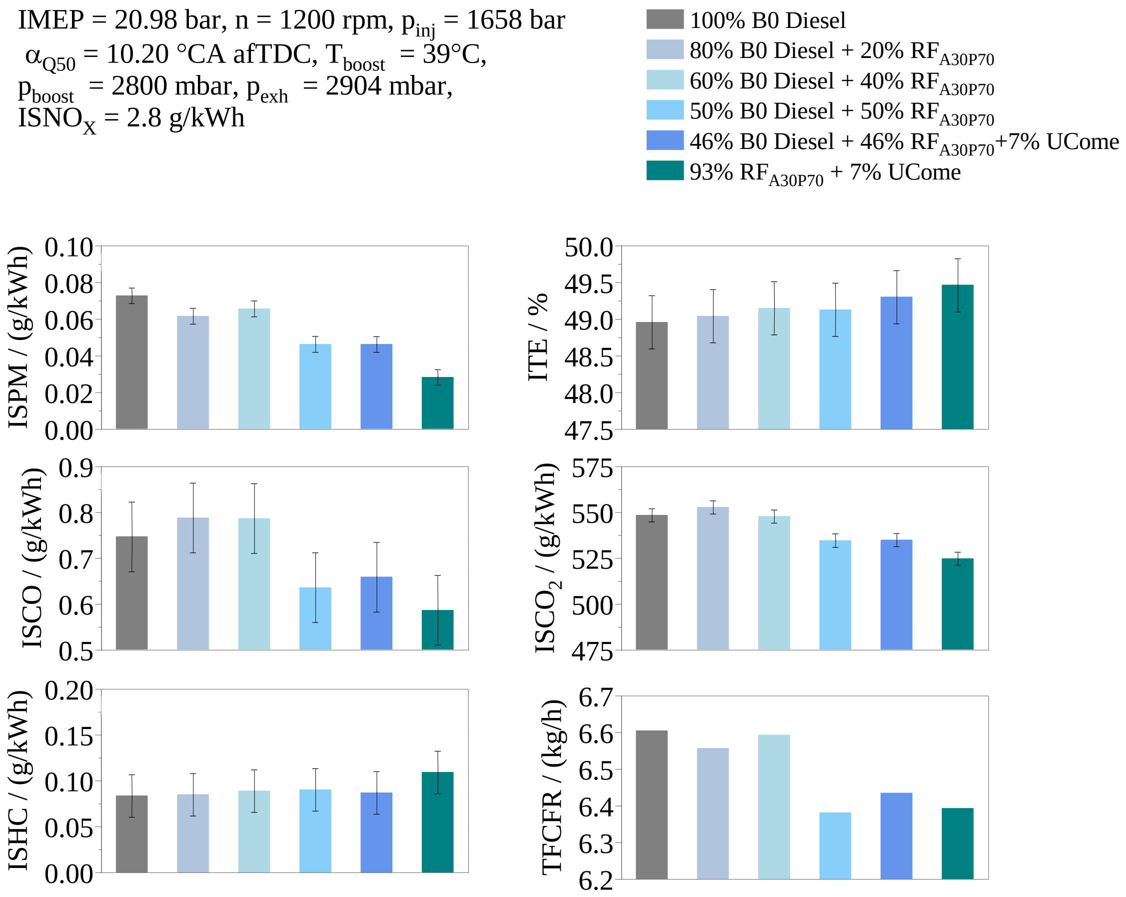

Figure 8: HD SCE results at best efficiency point for base NO$_X$ level, IMEP = 20.98 bar, n = 1200 min^{-1}, p_{inj} = 1658 bar, α_{Q50} = 10.2 °CA a. TDC, T_{boost} = 39 °C, p_{boost} = 2800 mbar, p_{exh} = 2904 mbar, ISNO$_X$ = 2.8 g/kWh

Also that this operating conditions an analysis of the losses has been performed. Overall, the findings are similar to the Cruise Point with lower engine load, while the differences between the fuels are even smaller at the best efficiency point.

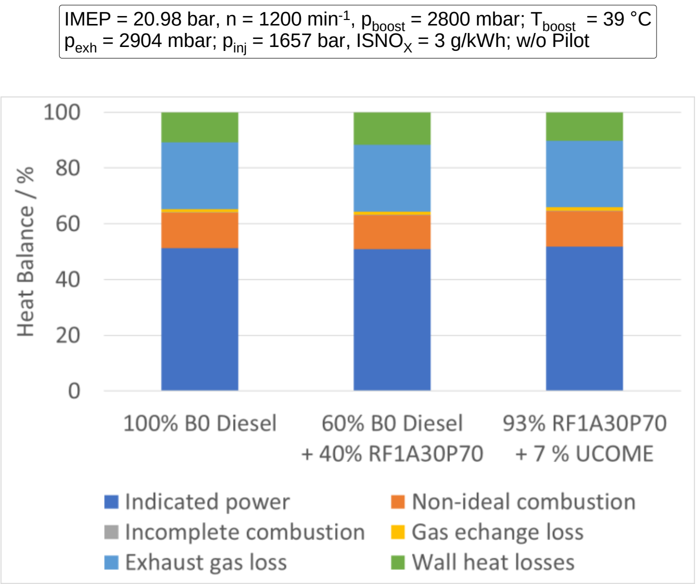

Figure 9: Share of losses at best efficiency point for base NO$_X$ level, IMEP = 20.98 bar, n = 1200 min-1, p_{inj} = 1658 bar, α^{Q50} = 10.2 °CA a. TDC, T_{boost} = 39 °C, p_{boost} = 2800 mbar, p_{exh} = 2904 mbar, ISNOX = 2.8 g/kWh

4 Discussion and Conclusions

4.1 4.1 DISCUSSION

Based on the described results it was decided that an online change of engine calibration based on the alcohol content of the fuel detected by the vehicle is not feasible. The possible benefits that could be gained by such an on-the-fly calibration adaption is not in line with the tremendous effort that would have to be taken by the OEMs. Moreover, the consortium is not aware of a market-ready sensor that is able to properly detect the share of higher alcohols in the fuel.

4.2 4.2 CONCLUSIONS

The potential of the novel drop-in biofuels containing high-Cetane (C_{11}-C_{21}) bio-hydrocarbons and (C_6-C_{11}) bio-alcohols was examined with regard to mixture formation, engine performance and emission reduction.

- The thermo-physical and physicochemical properties of fuel surrogates are estimated using models over a wide range of temperatures, featuring very good agreement with measured data.
- The fuel blend with 40 vol% REDIFUEL (i.e. RF_{A30P70} - alcohol of 30 vol% and a paraffinic content of 70 vol%) in diesel satisfies both the minimum requirement for Cetane Number and density stated by the EN590 norm.
- All the blends of REDIFUEL with diesel exhibit a marginal rise in efficiency and reduced engine out CO_2 emissions. Generally, the particulate matter, carbon monoxide and hydrocarbon emissions are reduced with an increase in the renewable drop-in fuel.
- The fuel blend with 40 vol% REDIFUEL in diesel exhibits a relative reduction in indicated specific particulate matter, indicated specific carbon monoxide, indicated specific hydrocarbon and CO_2 emissions by 12 %, 6 %, 18 %, and 2.7 % respectively with reference to diesel. A marginal rise in thermal efficiency by 0.6 %-points is noticed for this blend.
- All fuel blends enable a further reduction of engine out NO_x emissions at the usual trade-off between NO_x, PM, and efficiency.
- The slightly faster burning of REDIFUEL leads to lower exhaust gas enthalpy but increased wall heat losses. In total, the impact on engine efficiency is limited.
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Overall, the REDIFUEL blends show similar performance as diesel with reduced particulate matter, hydrocarbon and CO_2 emissions. This suggests that REDFUEL will help in a reduction in TtW CO_2 emissions and, thanks to its renewable nature to an overall reduction in WtT CO_2 emissions. Further, the blend with 40 vol% REDIFUEL in diesel satisfies the EN590 norm and can be on the immediate term used in current heavy duty fleets, without necessity for hardware adaptation or engine calibration.

5 Deviations from Annex 1

In contrast to the initially desired flexible adaptation of the engine calibration depending on the fuel’s alcohol content, in the Deliverable 3.6 additional fuel blends of REDIFUEL with diesel at different NO_x-levels have been investigated. Based on the described results it was decided that an online change of engine calibration based on the alcohol content of the fuel detected by the vehicle is not feasible. The possible benefits that could be gained by such an on-the-fly calibration adaption is not in line with the tremendous effort that would have to be taken by the OEMs. Moreover, the consortium is not aware of a market-ready sensor that is able to properly detect the share of higher alcohols in the fuel.

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

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Project partners:
1 - FEV – FEV EUROPE GMBH - DE
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3 - CSIC – AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS - ES
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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

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

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