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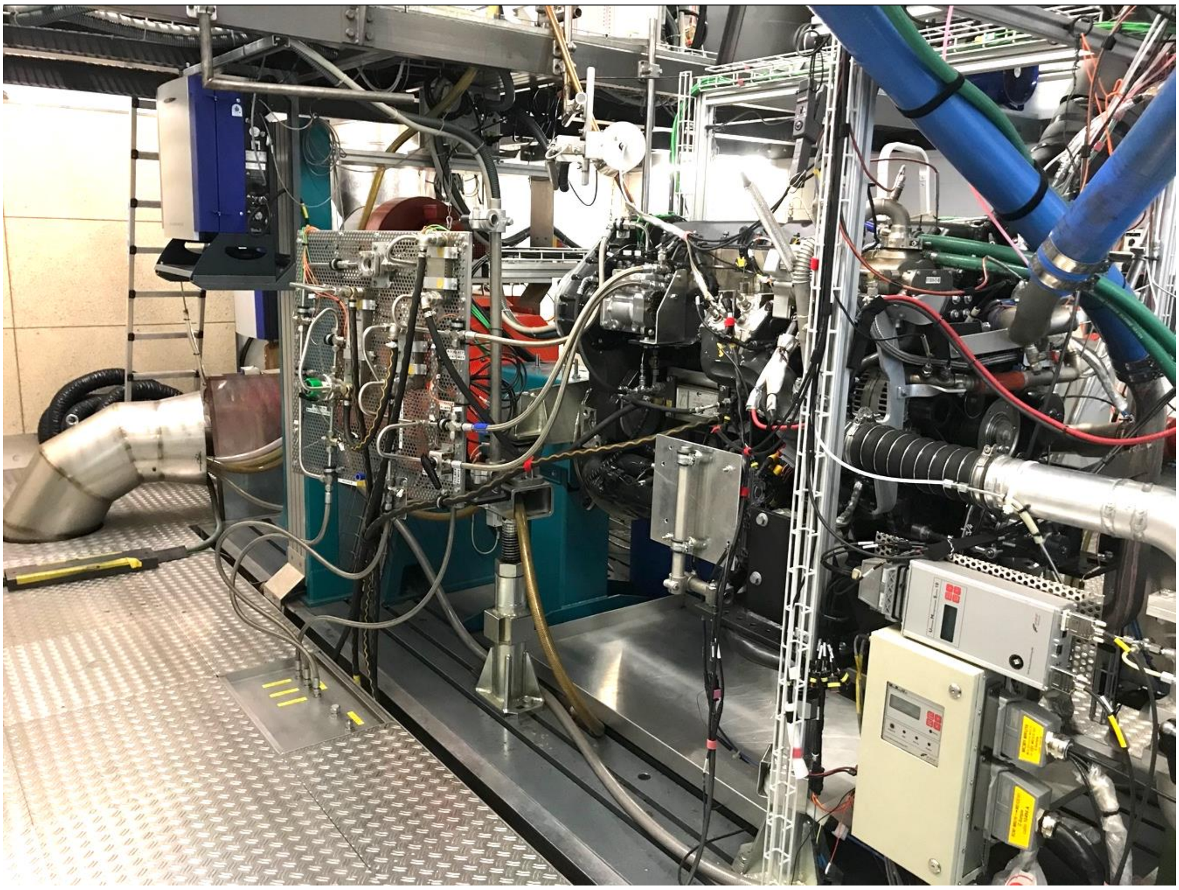
**Final report dated** 1. December 2021

# HDV-DME: Investigation of the suitability of DME as an alternative fuel in heavy-duty vehicles



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# Summary

This project is using the same engine platform as the one used in the previous SFOE funded project SI/501478-01 (Wirkungsgradsteigerung von Nutzfahrzeug-Dieselmotoren auf 50%). It represents a logical step for the development of a heavy-duty engine using an alternative fuel such as DME (Dimethyl-Ether).

DME is a well-suited fuel for compression ignition engines which can be produced from several renewable sources and has a volumetric energy density which is viable for high-power/long-haul heavy-duty applications. The H/C ratio of DME is significantly better than that of Diesel and thus the $CO_2$ emissions are lower. Since DME contains an oxygen atom, an interesting $NO_x$-soot-efficiency trade-off can be expected, especially if exhaust gas recirculation is used. The EGR (Exhaust Gas Recirculation) pump from the previous project allows high EGR rates quasi independently from the turbocharger operating point and thus extremely low engine out NOx emissions can be achieved without any soot.

All of the above-mentioned benefits of using DME as a fuel could be demonstrated in this project. Extremely low engine out $NO_x$ is possible whereas the Brake Thermal Efficiency (BTE) level decreases less than expected. For a target Brake Specific (BS) $NO_x$ engine out, less EGR is required with DME because late injection and low rail pressure is possible in the absence of a soot penalty. The injection / combustion chamber design proved to be very good, leading to extraordinary low particle levels in all relevant metrics (i.e. opacity, mass).

Main concerns like THC (Total HydroCarbon) or high Particulate Numbers (PN) emissions were not observed. All HC species emissions and PN in steady-state mode were far below the current legislation limit (EU6). Very low Particulate Matter (PM) emissions allow a different layout of the After-Treatment System (ATS) with a smaller particulate filter (only necessary for ashes from engine oil) located at the end of the ATS and not before the SCR. This can compensate the slightly lower exhaust temperatures compared to Diesel and therefore keep the SCR at about the same temperature level for good NOx conversion at low load.



# Résumé

Ce projet utilise la même plate-forme de moteur que celle utilisée dans le précédent projet financé par l'OFEN SI/501478-01 (Wirkungsgradsteigerung von Nutzfahrzeug-Dieselmotoren auf 50%). Il représente une étape logique pour le développement d'un moteur utilisant un carburant alternatif tel que le DME (Dimethyl-Ether).

Le DME est un carburant bien adapté pour les moteurs à allumage par compression qui peut être produit à partir de plusieurs sources renouvelables et a une densité d'énergie volumétrique qui est viable pour les applications poids lourds à longue distance. Le rapport H/C du DME étant plus favorable que celui du carburant diesel, les émissions de $CO_2$ à charge équivalente sont donc plus faibles. Étant donné que le DME contient un atome d'oxygène, un compromis intéressant entre les NOx et la suie peut être espéré, en particulier si la recirculation des gaz d'échappement est utilisée. La pompe EGR de l'ancien projet permet des taux EGR élevés quasi indépendamment du point de fonctionnement du turbocompresseur et ainsi des émissions de NOx extrêmement faibles peuvent être obtenues sans aucune suie.

Tous les avantages mentionnés ci-dessus concernant l'utilisation du DME comme carburant ont pu être démontrés dans ce projet. Un NOx spécifique extrêmement faible en sortie moteur est possible tandis que le rendement thermique du moteur diminue moins que prévu. Pour une valeur cible de BS NOx en sortie moteur, moins d'EGR est requis avec le DME car une injection tardive et une Plus faible pression d'injection sont possibles en raison de l'absence de pénalité de suie. Heureusement,

la conception de la chambre d'injection / de combustion s'est avérée très bonne, ce qui a conduit à des niveaux de particules extrêmement bas à tous égards (c'est-à-dire opacité, masse).

Les principales préoccupations telles que les émissions élevées de THC ou de PN n'ont pas été observées. Toutes les émissions d'espèces de HC et les nombres de particules (steady-state mode) étaient bien inférieurs à la limite légale actuelle (EU6). De très faibles émissions de PM permettent une disposition différente du système de post-traitement (ATS) avec un filtre à particules plus petit (nécessaire uniquement pour les cendres d'huile moteur) et de le placer à la fin de l'ATS et non avant le SCR. Cela peut compenser les températures d'échappement légèrement inférieures par rapport au diesel et donc maintenir le SCR à peu près au même niveau de température pour une bonne conversion des NOx à faible charge.

# Main Findings

The effort for hardware purchasing and software implementation as well as layout and setup of the test site infrastructure was higher than expected. The layout of the low-pressure fuel circuit was a challenging topic as phase change from liquid to gaseous DME needs to be avoided for all conditions of engine operation. The chosen layout worked very well during the whole project.

The potential of DME in compression ignition engine as a fuel for clean combustion and high efficiency, published in many papers, could be confirmed or even exceeded. The heavy-duty Cursor 11 (C11) DME prototype engine showed uncritical THC levels – in contrast to literature of previous research in this field where high THC levels were reported. This can be attributed to the careful design of the piston bowl and the injector nozzle using 3D CFD tools. Concerns about Particulate Number emissions have not been noticed. This type of emission was also far below the legislation limit even without a DPF.

The current C11 layout can be taken as a basis for further DME application. One immediate decision of the FPT Powertrain Engineering management, due to the very promising results, is to setup a demonstration project on a Euro VI Stralis heavy-duty vehicle operating in daily commercial operation. This would be a kind of follow-up project.

The most appealing result is the $CO_2$ saving potential of 10-12% Tank-to-Wheel (TtW) at the same efficiency compared to Diesel, even when fossil-based DME is used. Other relevant Green-House-Gas (GHG) Emissions like $N_2O$ or $CH_4$ are negligible. As the production of renewably sourced DME is ramped up, the gradual replacement of fossil-based DME would lead to increasing $CO_2$ savings. Installing retrofit kits on existing vehicles with modest adaptations to replace Diesel (details in chapter 2.2.7 on page 22) could be an immediate or at least midterm contribution to $CO_2$ emission reduction.

# Contents

# Abbreviations

| | |
|---|---|
| AHRR | Apparent Heat Release Rate |
| ATS | After Treatment System |
| BSFC | Brake Specific Fuel Consumption |
| BS $NO_x$ | Brake Specific $NO_x$ |
| BS Soot | Brake Specific Soot |
| BTE | Brake Thermal Efficiency |
| CA | Crank Angle |
| CGI | Compact Graphite Iron |
| CR | Compression Ratio |
| DOC | Diesel Oxidation Catalyst |
| DME | Dimethyl-Ether |
| DoE | Design of Experiments |
| EGR | Exhaust Gas Recirculation |
| FEP | Fuel Economy Package (FEP2 has higher friction than FEP3) |
| FID | Flame Ionization Detector |
| FTIR | Fourier Transform Infra-Red |
| GHG | Green House Gas emission |
| HDV | Heavy-Duty Vehicle |
| HRR | Heat Release Rate |
| HW | Hardware |
| ICE | Internal Combustion Engine |
| MFB10 | Mass Fuel Burnt 10% |
| MFB50 | Mass Fuel Burnt 50% |
| MFB90 | Mass Fuel Burnt 90% |
| NDIR | Non-Dispersive Infra-Red |
| PCP | Peak Cylinder Pressure |
| PIN | type of nozzle |
| PPC | Partially Premixed Combustion |
| PN | Particulate Number |
| PM | Particulate Matter |
| pRail | injection Rail Pressure |
| rDME | renewable Dimethyl-Ether |
| RPM | Rotation per Minute |
| SCR | Selective Catalytic Reduction |
| SOIe | Start Of Injection electric |
| SW | Software |
| THC | Total Hydrocarbon (including all species) |
| TtW | Tank-to-Wheel (tailpipe) |
| VGT | Variable Geometry Turbine |
| WtT | Well-to-Tank (including production and distribution) |
| WtW | Well-to-Wheel (including production, distribution and tail pipe) |

# 1 Introduction

## 1.1 Background information and current situation

In the future, $CO_2$ emissions for the HD transport sector will be regulated as well. Lowering the engine out $CO_2$ emissions will be crucial to meet more stringent legislation limits in the future. DME has the potential to meet both, $CO_2$ and $NO_x$, emission limits and can therefore be a promising alternative to overcome the need for a clean fuel for internal combustion engine to replace fossil fuels [1][2][3][4]. At the beginning of this project we, FPT and Empa, were already convinced about DME's potential but it was not clear how the global situation would evolve. Recently we are facing a fast-growing interest for DME in general, especially for renewable DME to be used in the agriculture sector with circular economy.

In the on-road transportation business the general tendency in the last years was towards electrification and hydrogen and for some applications LNG/CNG (but still far away from big market share). The slow infrastructure developments for electrification and hydrogen (far not reaching the required pace) are leading to the realisation that internal combustion engines will be still required for a lot of applications in the decades to come. For this reason, alternative fuels are more and more coming back into focus. As demonstrated in this project, DME is a very promising candidate for heavy agriculture machines as well as heavy long-haul transport, considering upcoming stringent emission limits.

There is an additional reason within Switzerland to consider alternatives to electrification: the concern of an Energy supply problem during winters of the next years due to restricted access to the European electricity market and additional electric energy consumers demanding (heat pump, e-cars, trucks?,…) [5]. The wind power potential in Switzerland is very limited and the hydropower potential is already largely used. Photovoltaic will help but not solve the problem. Heavy-duty transport with ICE can mitigate the problem. The countries surrounding Switzerland are facing the same challenge. Studies from Germany, for example, show that the use of renewable hydrocarbons will be extremely important to reach a net-zero goal in 2050 [6].

In the last few months, the interest for renewable DME (rDME) seems to be growing globally. We have been contacted by Researchers (Fraunhofer Chile) that are developing large scale and low-cost Wind and PV Power-to-Liquid plants in Chile (rDME/rMethanol). Renewable Methanol is more suitable for shipping to Europe and the conversion to rDME is very effective and not a very costly process. To produce 1 ton of DME (lower heating value 28.4 MJ/kg) about 1.4 ton of Methanol (lower heating value 19.9 MJ) is required. At the end, DME stored at 6 bar can be a Hydrogen carrier as for the same equivalent volume it contains about 6 times more energy than Hydrogen at 350 bar (factor 3 at 700 bar) and is much easier to handle and store. Methanol and liquid DME contains respectively 39.7% and 23.3% more Hydrogen in mass than liquid Hydrogen.

Existing LPG infrastructure could be converted to DME as it needs to be stored at the same pressure (5-6 bar).

## 1.2 Purpose of the project

Purpose: the optimization of a heavy-duty engine for the use of DME and the fundamental understanding of diffusion type of combustion with DME in a CI engine. Due to a very favourable $NO_x$/soot-trade-off as this alternative fuel contains oxygen, the main focus is high EGR rates for low engine out $NO_x$ emissions as well as Diesel-like brake thermal efficiency. The EGR pump at the turbocharger's high-pressure side was already developed within the previous project on the same engine and it can help to realise high EGR rates under all operating loads at a reasonable efficiency level.

DME ($C_2H_6O$) is a well-recognised alternative fuel with interesting properties and providing the lowest $CO_2$ emissions of all hydrocarbon fuels since it can be used in efficient compression ignition engines due to its high cetane number of around 55. Methane $CH_4$ has an even better H/C ratio but the benefit is depleted by the lower efficiency of spark ignited stoichiometric combustion compared to lean burn CI engine with DME.

## 1.3 Objectives

**From Research project tender (1.8.2018)**

Objectives: "… Within this project, a modern heavy-duty engine will be optimized for the use of DME."

Deliverables:

- Performance, Combustion efficiency and emission results with base engine
- Documentation of parts modification, new proto parts
- Performance, Combustion efficiency and emission results with base engine and adapted engine oil specs
- Performance, Combustion efficiency and emission results with final layout

# 2 Description of facility

## 2.1 Experimental facility (at Empa)

### 2.1.1 Fuel supply system

DME used for this project is produced by Europe's largest producer Nouryon in The Netherlands and distributed via a retailer in northern Italy to Dübendorf. DME is delivered in so-called Ton Cylinders. This are steel cylinders with 930 litres volume and approved to pressures up to 30 bar. These cylinders are filled with around 540 kg DME each and since the pressure in the cylinders is around 5 bar at 20°C (see Figure 1), they have an adequate safety margin for temperatures up to 90°C.

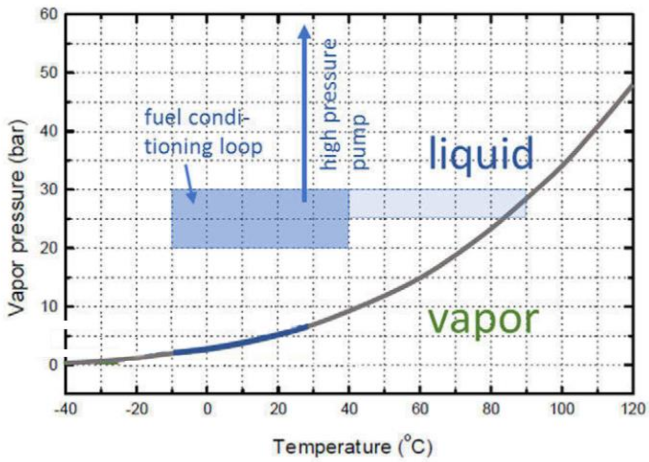


Figure 1: Vapor pressure curve for DME

In order to minimize transport costs for DME, storage room for the DME cylinders has been designated and updated to fulfil the explosion prevention regulations for so-called class 2 chemicals. Figure 2 shows the storage situation as of December 2020 with 10x full and 8x empty DME cylinders.


Figure 2: Storage of DME cylinders at Empa's ex-prevented storage room

A DME supply concept has been designed, built and put into operation in 2020. The DME supply system has the following characteristics :

- A supply container with fire resistance class EI 90 is placed outside of the "Motorenhaus"-building of Empa (4).
- A DME cylinder is placed inside the container and connected to the supply system (Figure 3).
- An Ex-Zone 1 is defined inside the container, which means that all components have to comply with ex-regulations, the container is ex-observed and a defined air exchange is applied.
- The container contains the technical installations for a safe DME supply of up to 200 kg/h (Figure 4).
- The container is connected to the gas- and fire-alarm system of the test bench and reacts accordingly to gas leaks or fire situations.
- All piping in the building is done with stainless steel, no connections are allowed, all pipe connections are orbitally welded.
- Automatic and fail-save shut-off valves are placed on both sides of the supply system, they must guarantee a safe dumping of DME to the atmosphere in case of an unexpected pressure increase (e.g. as a consequence of fire in the building)
- The container is climatized to keep the thermal conditions for all installations at an appropriate level.

The build-up and commissioning of the infrastructure had a large delay in this project. Reasons for this were an extraordinary long time to receive the construction permit by the city of Dübendorf, unexpected problems with components related to DME incompatibility of materials, some components which did not meet the producer's specifications and had to be redesigned as well as delivery delays due to the 2020 pandemic. However, once the problems had been fixed, the DME supply proved to work flawlessly and experimental results could be efficiently produced right away. All these complications led also to a large increase of the installation costs. Initially, as stated in the BFE project application, cost estimations for the DME supply were in the region of 100'000 CHF. At the end, the real costs summed up to around 400'000 CHF. Since Empa has identified DME as a strategically important fuel to reach climate goals for heavy-duty transport, these costs were fully covered by Empa as an opportunistic investment to future projects.

Figure 3: DME supply container

Figure 4: Pneumatic DME delivery pump plus other technical installations inside the container

The supply system's schematic is shown in Figure 5. The liquid DME phase is taken from the supply cylinder and pumped, using a custom-made twin cylinder pneumatic pump, with a pressure of 26 bar. This high-pressure level is chosen to avoid problems from cavitation in the following installation. In a vehicle, where the supply is very close to the engine, a much lower supply pressure can be chosen. From there, the engine's low-pressure fuel supply is connected (22). Additionally, two backflow paths are present: one for the regular fuel backflow of the injectors and a second, equipped with a release valve, to enable DME release in case of emergency. The fuel consumption of interest is the difference between supply and backflow, high-precision coriolis mass flow meters are mounted in the supply- as well as in the backflow pipe.

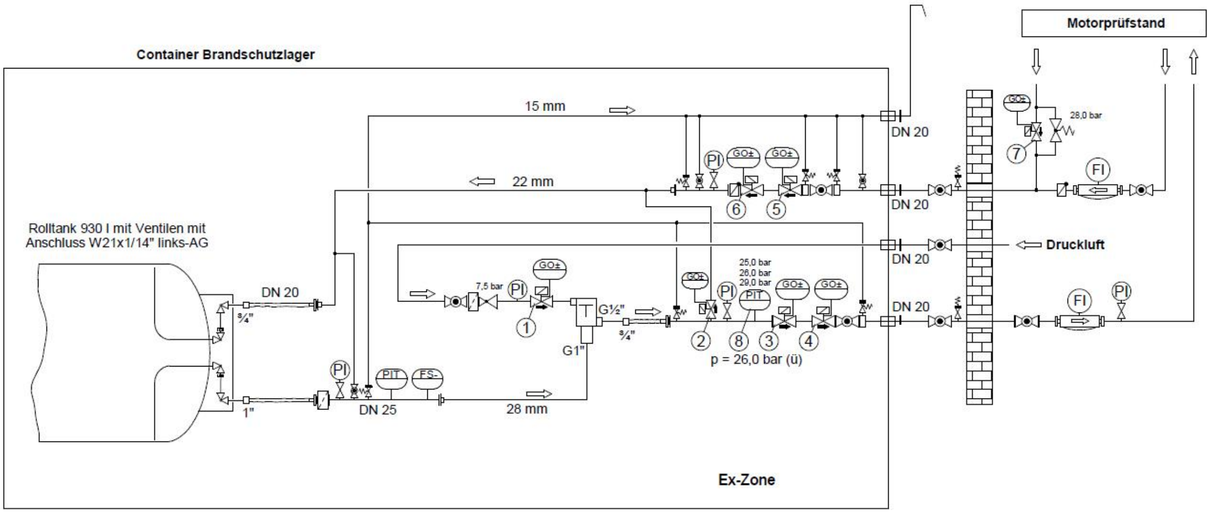



Figure 5: System schematic of the DME supply installations

### 2.1.2 Engine test facility

Figure 6 and Figure 7 show the installation of the Cursor 11 engine, mounted on Empa's test bench, from both sides. On the air side, the low-pressure fuel circuit panel is visible where the supply pressure of 26 bar is reduced to about 10 bar and fed to the common rail pump. Also visible is the EGR pump (see detailed description in section 2.2.1). On the exhaust side, the engine is equipped with the diesel engine’s after-treatment system consisting of a diesel oxidation catalyst (DOC), a diesel particle filter (DPF), a selective catalytic reduction section (SCR) and an ammonia clean-up catalyst (CUC). However, as experiments show (see section 4.1), the engine’s raw emissions are much lower with DME than with diesel, so a simpler after-treatment setup is very likely to be sufficient to fulfil the most stringent on- and off-road emission limits.
Based on that, the decision was made to switch to a modular research type exhaust after-treatment system with adapted sizing, updated coating and setup of the SCR and DPF sections. In contrast to the highly integrated series type diesel system in Figure 7, this allows for the exchange of or switch between single sections as well as measurement possibilities for temperature and exhaust gas concentrations between the sections. Figure 8a and Figure 8b  shows the adapted after-treatment system with the single sections DOC, SCR and DPF and the routing of the exhaust gases within the system. The most significant change, apart from sizing, is the location of the DPF downstream of the SCR part due to the very low soot production of DME combustion and therefore no need for frequent active regeneration cycles.

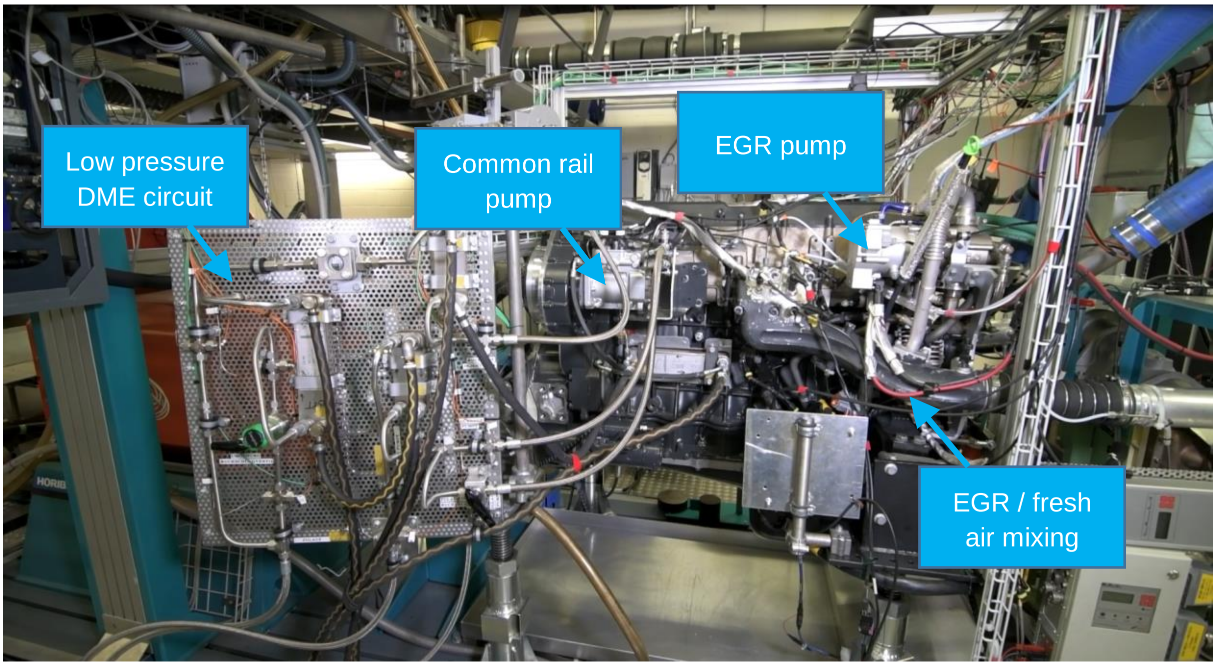


Figure 6: Engine's air side

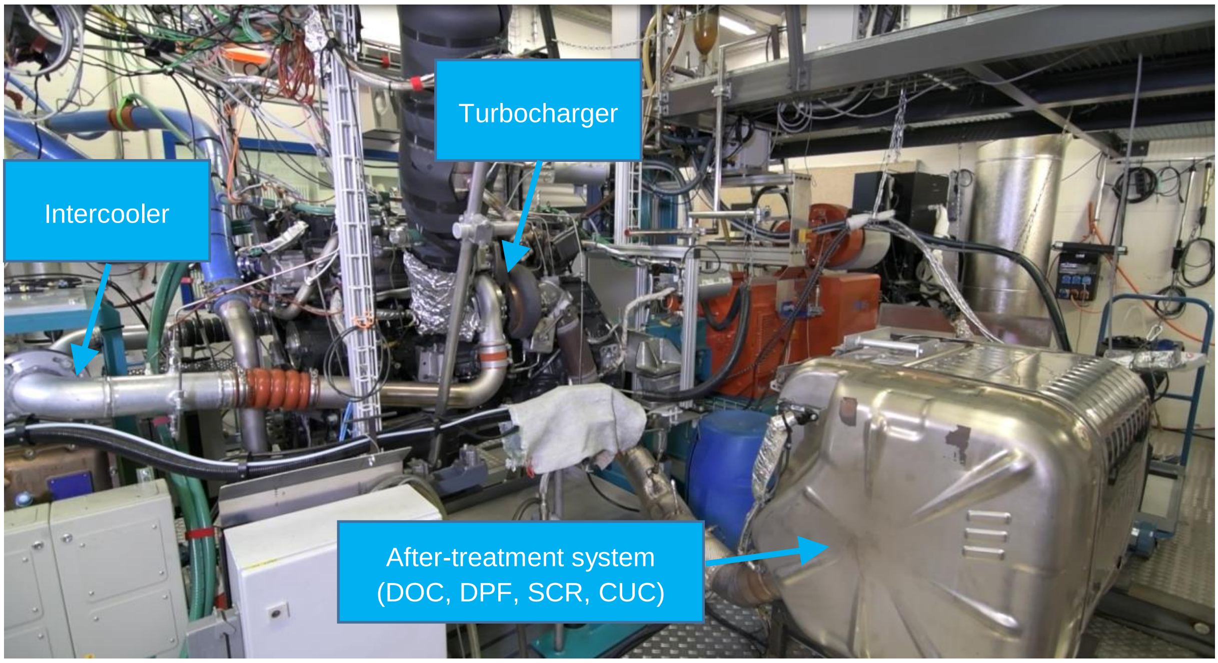


Figure 7: Engine's exhaust side (highly integrated series type diesel system)

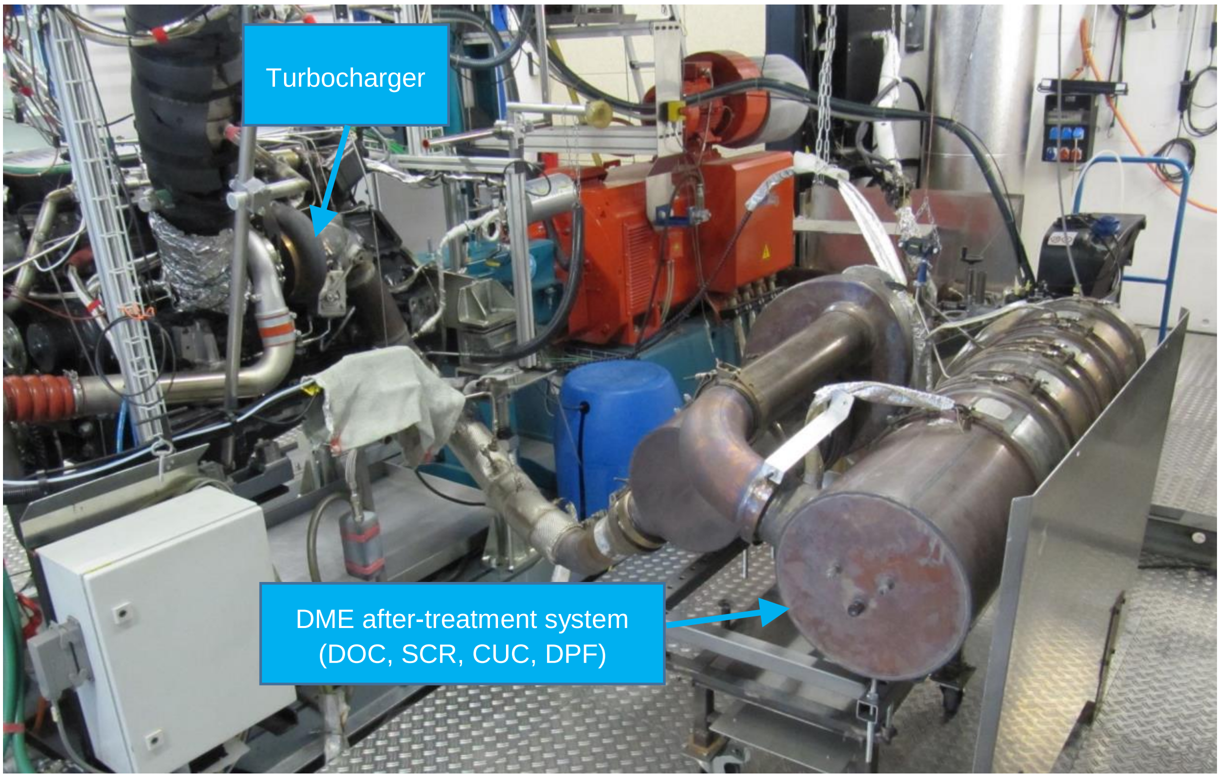



Figure 8a: Engine's exhaust side with DME specific modular research ATS system

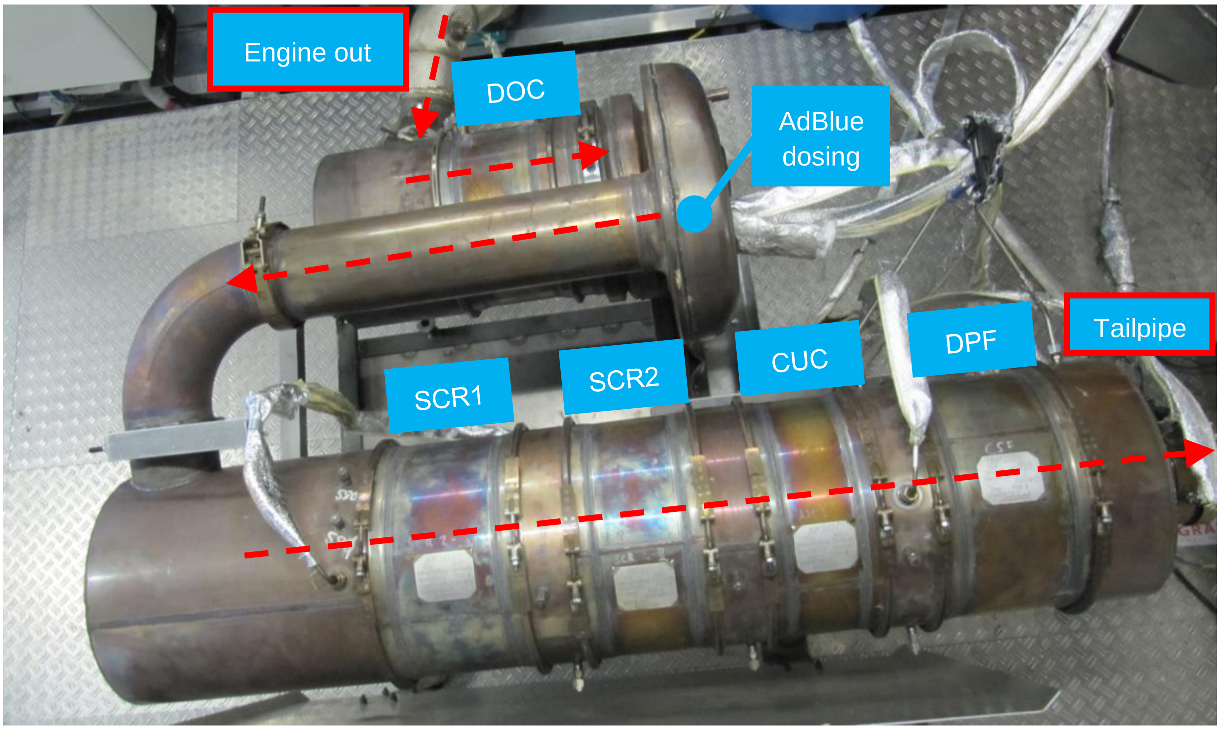



Figure 8b: Exhaust gas routing within modular research ATS for DME operation

## 2.2 Engine (FPT Cursor 11)

The base engine as shown Figure 9 is an FPT Cursor11 heavy-duty 6 cylinders in-line diesel engine developing 338 kW and a maximum torque of 2300 Nm, equipped with a cooled High-Pressure EGR system. The engine was used in a previous project to scout various technologies to improve fuel consumption (SI/501478-01/ "Wirkungsgradsteigerung von Nutzfahrzeug-Dieselmotoren auf 50%"). The peak cylinder pressure can reach 250 bar in order to accommodate a high compression ratio of 20.5:1.

Figure 9: FPT Cursor11 with high pressure EGR used a base engine

### 2.2.1 EGR pump

An electrically driven volumetric EGR pump (Figure 9a), which is installed after the EGR cooler was developed in previous project together with Eaton in order to control the EGR level accurately within the whole engine map to lower the NOx emissions. The pump reduces the impact of EGR on the gas exchange efficiency by avoiding throttling the turbine exit to create enough pressure difference between the exhaust and intake side to drive EGR

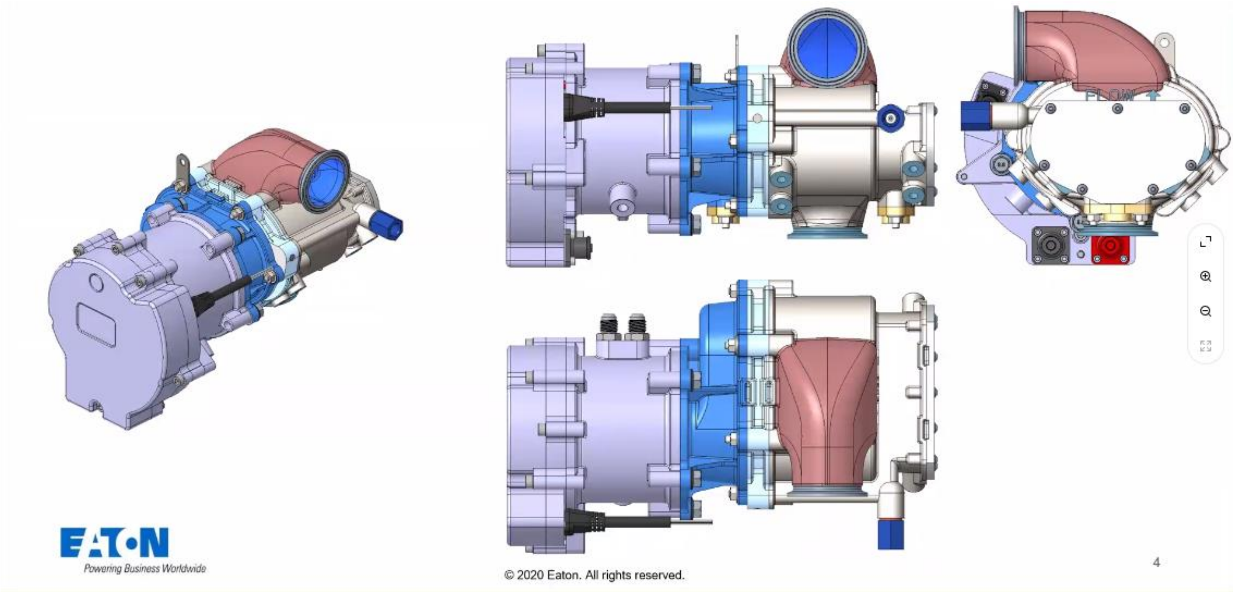



Figure 9a: EGR pump Eaton Generation 2, TRL 5

Figure 10 shows the nice final integration of the EGR pump on the engine where it takes the space freed by the removal of the diesel fuel filters. NVH measurements of the EGR pump showed very low level of vibrations on the pump itself and the e-motor.

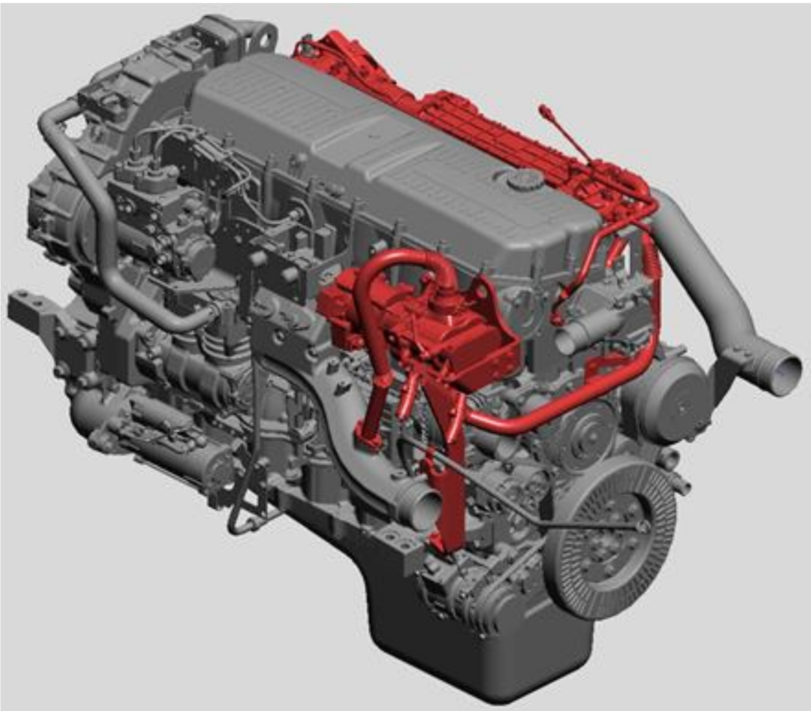


Figure 10: New adaptation of EGR pump on engine

The Air path layout for the DME engine can be seen Figure 11. The turbocharger used is state of the art, reaching 80% efficiency in best point of the compressor map. The Non-Return valves (NRV) located after the EGR cooler increase the pressure loss in the high pressure EGR circuit but are able to reduce the pressure fluctuations from the exhaust side which can affect the pump operation and control at low engine speed. For this last reason, it was decided to keep them.

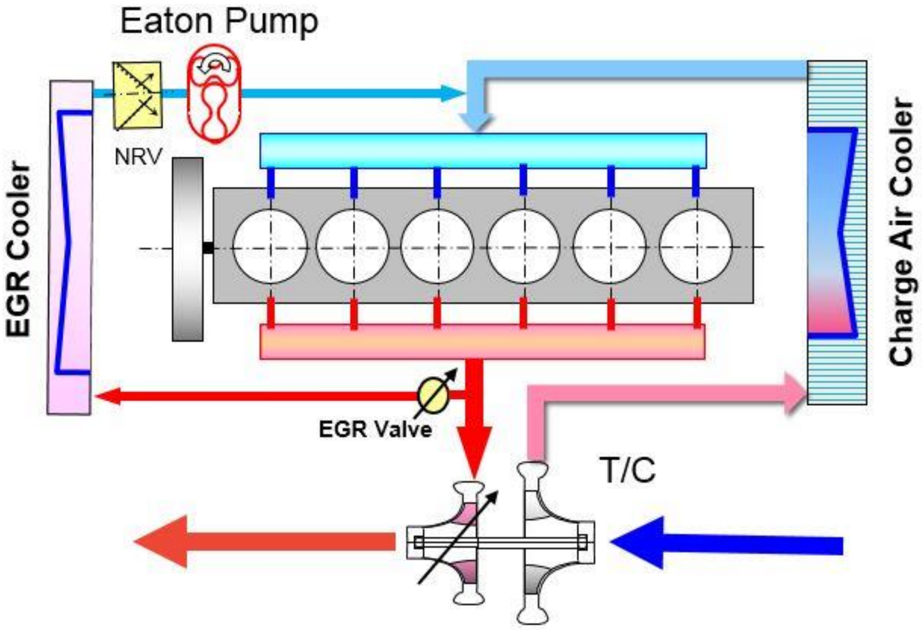



Figure 11: Air path schematic of the DME engine

### 2.2.2 High-pressure pump and injectors

Fuel injection system adaptation to DME: due to low lubricity of DME, the high-pressure pump needs to have lubricated plungers [4]. Known projects up to now used lubricity additives in DME to guarantee a proper common rail pump lubrification. The goal of this project is to avoid additivities to guarantee easier fuel handling and, more importantly since DME is a very pure fuel, to avoid potential pollutant emissions such as nano particles. The re-design of the common rail pump for external lubrification was a big issue which needed very high effort on FPT side in terms of convincing Bosch about potential as well as giving technical support for the low-pressure part of the fuel system. Additionally, due to lower heating value by factor 1.8 and limited rail pressure capacity (max. 1300; high compressibility of DME), the injector flow rate needs to be increased by factor 2.5 to achieve similar injection duration compared to Diesel. This challenge took some efforts but, with a large delay from Bosch side, the necessary components were delivered. Additionally, the engine control unit needed to be switched from EDC17 used in the previous project to MD1 due to requirement of the electronic suction valve control of the high-pressure pump. This needs replacement of wiring harness as well as an update of the main relay unit that controls the engine from the test bed.

Tests on injection rig in Arbon have been performed with Bosch in January 2020. The system did not work properly due to software bugs. After debugging, the next trial had been done end of March with virtual support from Bosch due to Covid-19 and was successful.
For the first firing event at Empa beginning of July, Bosch was not allowed to join on site due to the pandemic situation.

During the test cell activities, some issues have occurred:

1. When filling the low-pressure fuel system, the first time, a certain leakage at the electronic suction valves on the high-pressure pump has been found (Figure 12 on the left). Leakage amount has been considered not to be critical and not a showstopper for first firing. Communication with Bosch resulted in their statement not having mounted DME-resistant O-ring material. After mounting O-ring type B (see below), the problem was solved.

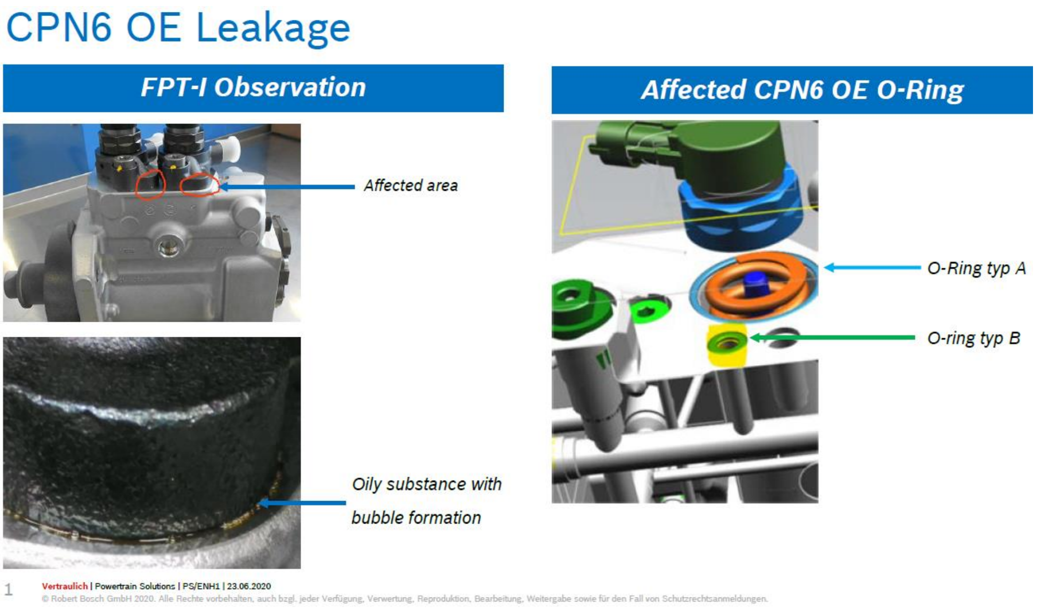



Figure 12: CPN6 DME leakage

2. Another issue at the beginning was the Rail pressure not being stable in all conditions. This made support from Bosch on site necessary which happened mid of August. After this intervention, the behaviour of the complete system was like expected.
3. In spring 2021 the preparation of WP4 (Emission legislation compliance) has been interrupted by a leakage problem on the high-pressure pump. It took about two months to solve the leakage problem as the first approach (O-ring exchange at one of the electronic suction valves) did not solve the problem. The reason at the end was a crack in the welding of the pump element stator of the suction valve no. 2 (see Figure 13). For safety reasons both suction valves have been changed.

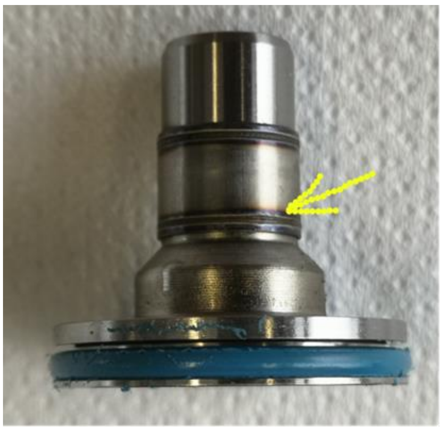


Figure 13: pump element stator eSV2

4. Around the same time a Rail pressure monitoring failure during WHTC test has been found. An expert from Bosch visited Empa to solve this rail pressure monitoring problem. It was just a calibration modification necessary and after two days everything worked fine. WHTC measurements could be performed. This was the base to effectively start WP4.

### 2.2.3 Low-pressure fuel circuit

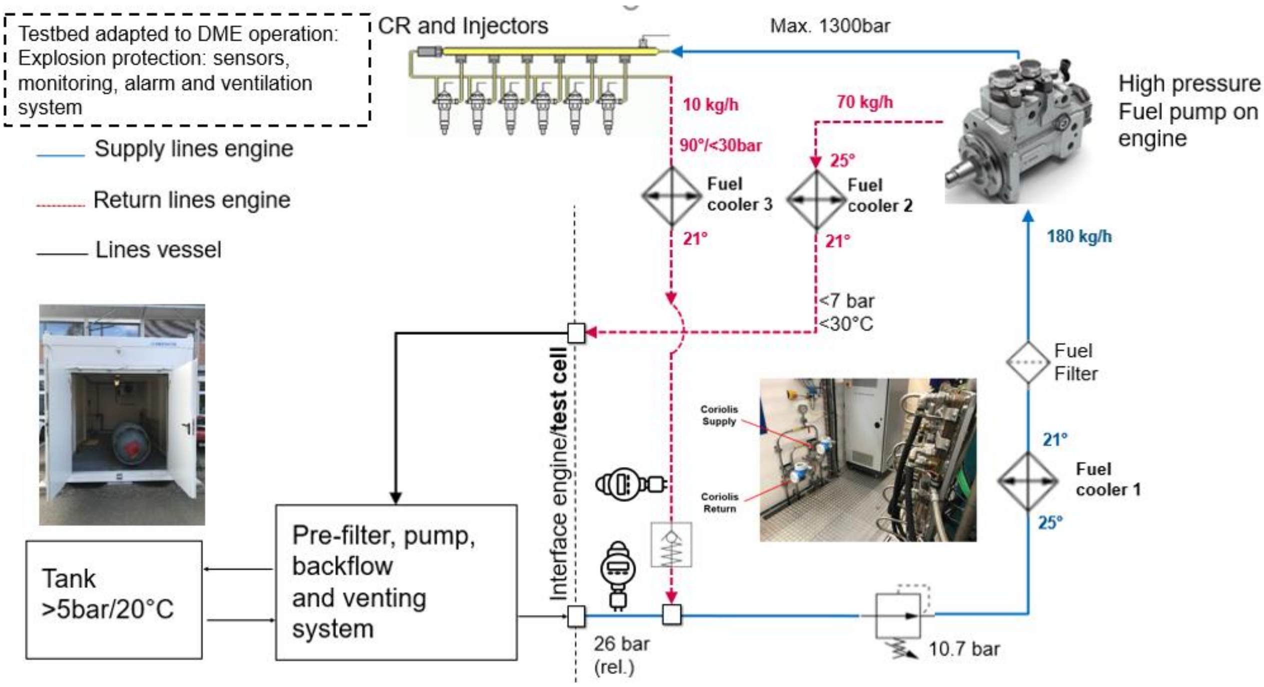



Figure 14: low pressure fuel circuit (simplified scheme without relevant details)

Problems found and solved during first phase:

- Too high pressure-drop over the 5 µm fuel filters (3 in parallel). Reason: contamination by corrosion inside the DME cylinders (900l drums in the supply container). Later it was detected that the cylinders are made of carbon steel instead of stainless steel. Carbon steel can be used but then it must be coated with a special zinc-coating protective layer to prevent negative corrosion. It was agreed with the DME supplier, that future deliveries of DME will be done only in new cylinders. For safety reason, an additional pre-filter on the supply side has been installed.
- High-pressure pump backflow from the pump lower than 7 bars →additional valve necessary
- Low pressure control valve 25/12bar not fully capable to reach requirements → supplier provided better suited valve

### 2.2.4 Valve and seat material

New valve and seat material mounted on cylinder 1, 3 and 5 while cylinder 2, 4, 6 remained with standard material to check difference after about operation hours. Depending on the valve gap behaviour over time and after dismantling and inspection it can be decided if this is really necessary or if the standard material is compatible.

| *DME* | p/n | | q.ty | Piece price (€/each) |
|---|---|---|---|---|
| Cursor 11 | *V78388 PB* | Intake valve | **12** | € 120,00 |
| Cursor 11 | *V78389 PB* | Exhaust valve | **12** | € 130,00 |
| Cursor 11 | 5802321088 | Spring retainer | **24** | € 16,00 |
| Cursor 11 | 5802321110 | Cotters | **48** | € 5,00 |

Table 1: Details about DME specific valves and cost

### 2.2.5 DME dedicated engine oil (Product V19.225O SAE 0W/20)

We have pushed together with Motorex to close the additives engineering for a DME-dedicated engine oil before test bench activity start. Additionally: Elastomer-Tests or at least crosscheck against Cursor 11 sealing material specs (i.e. Elongation and Tensile strength as well as Shore-A, Volume and Mass extension) regarding DME use had to be done.
Test run of new oil with Diesel (in BTE50% project) already done with oil samples analysis after some running hours to have a base for comparison. After the first 10-20 hours with DME the oil was again changed and then oil samples have been taken periodically according to Motorex recommendations. The samples have been sent to Motorex for analysis (see table 2 below)

| **Einsatzdauer h** | **1h** | **52** | **102** | **155** | **204** | **254** | | **Differenz Ende zu Anfang** |
|---|---|---|---|---|---|---|---|---|
| TAN | 2.00 | 1.76 | 1.70 | 1.70 | 2.00 | 2.00 | mgKOH/g | **0.0** |
| TBN | 13.90 | 13.20 | 12.70 | 12.10 | 11.70 | 11.60 | mgKOH/g | **-2.3** |
| Oxidation | 1 | 3 | 3 | 2 | 2 | 1 | A/cm-1 | **0.0** |
| Visk 100°C | 8.8 | 8.7 | 8.7 | 8.7 | 8.7 | 8.6 | mm2/s | **-0.2** |
| Fe-Wear(ppm) | 1.0 | 9.0 | 14.0 | 22.0 | 39.0 | 47.0 | ppm | **46** |
| Cu-Wear (ppm) | 1.0 | 7.0 | 12.0 | 14.0 | 17.0 | 26.0 | ppm | **25** |
| P-conc(%) | 0.0845 | 0.0842 | 0.0823 | 0.0808 | 0.0804 | 0.0793 | % | **-0.0052** |
| S-Conc (%) | 0.2194 | 0.2188 | 0.2136 | 0.2089 | 0.2016 | 0.1832 | % | **-0.0362** |

Table 2: Details about engine oil analysis by Motorex

### 2.2.6 Overview about engine modifications for DME

Figure 15 gives an overview about the parts to be adapted for DME, which are in particular (from top left to bottom right):

**High pressure EGR system with EGR pump**: to allow very high EGR rates independently from the Turbocharger operating point (without it is only possible as long exhaust pressure is higher than boost pressure)

**Injector nozzles with increased flow**: necessary due to lower energy density of DME compared to Diesel (factor 1.8) and limited rail pressure. The total flow increase factor is around 2.5

**DME resistant sealing type**: all O-rings in contact with fuel need to be changed to appropriate material Teflon/Polytetrafluorethylen (PTFE).

**Valve and valve seat material** (page 21 and 22): the valve clearance difference between the standard and the special material at the end of the test was neglectable, therefore this point seems not to be a mandatory one, at least for this engine.

**Optimized turbocharger for EGR**: due to the high EGR rate another turbo compared to the base engine was needed

**Piston with optimized bowl shape and higher compression ratio**: need to get optimum combustion results regarding efficiency and emissions.

**Lubricated Bosch high pressure fuel pump**: usually Diesel high pressure pumps are lubricated by the fuel itself. Due to the low lubricity of DME, the pump needs to be engine oil lubricated

**DME dedicated engine oil**: particular adaptation of the additive mixture to DME properties to ensure same life time and oil consumption behaviour like Diesel version

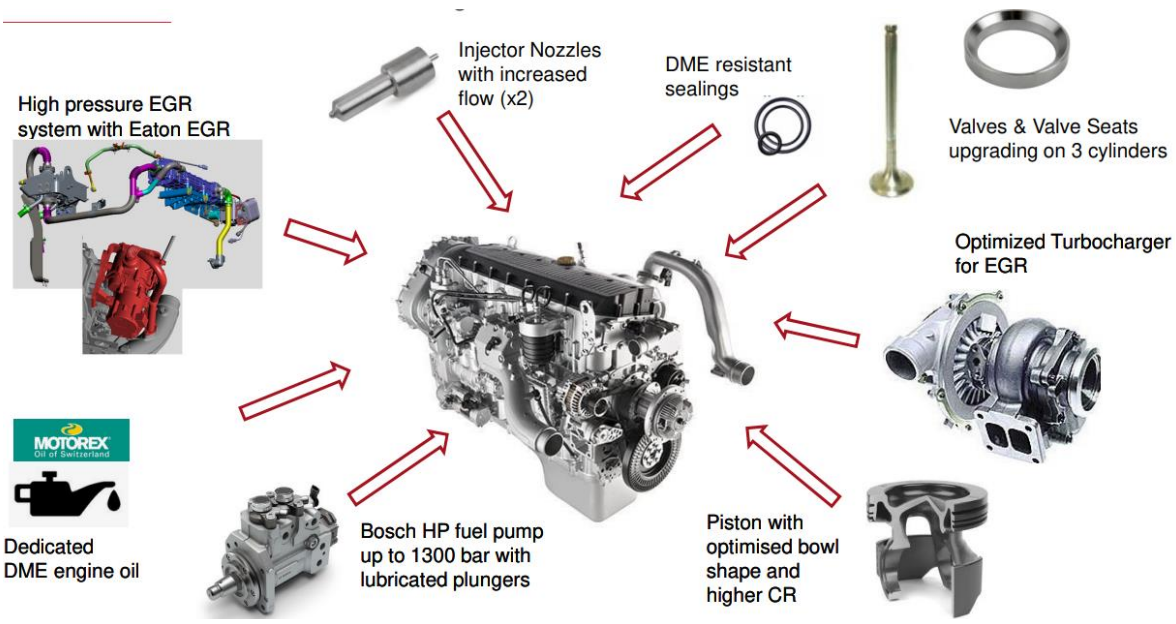



Figure 15: Engine components to be modified for DME

### 2.2.7 Overview about possible engine and vehicle modifications for DME/Diesel blend (Retrofit midterm solution)

Figure 16 contains the same modifications like the previous figure for the engine but completed with the necessary adaption when it comes to a vehicle application, such as:

**Low pressure fuel pump**: in order to keep the fuel always liquid under all ambient conditions (very hot), the feed forward pressure needs to be at a level of about 26 bar (see Figure 1 on page 10)

**Fuel pressure regulator valve**: to control pressure to the target high pressure pump inlet limit (in case of the used Bosch CPN6 pump at 10.7 bar)

**Additional fuel coolers**: the temperature in the high pressure pump and in the injectors return line can achieve high values (in case of the injectors around 80°C due to the rail under cover). To avoid vapor lock, all return lines need to be cooled accordingly (see Figure 1 on page 10). An additional cooler in the feed forward line to keep the fuel always at 20-25° is recommended as well.

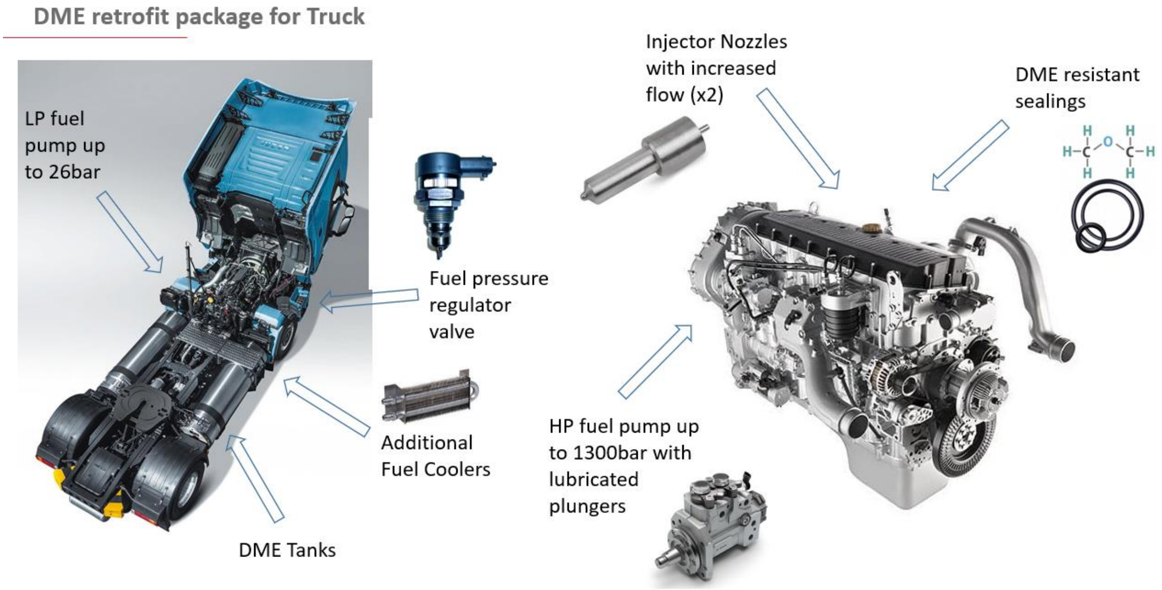



Figure 16: Engine and vehicle components to be modified for DME Retrofit solution

# 3 Procedures and methodology

## 3.1 $CO_2$ reduction potential of DME

Main purpose was to find an alternative fuel for high-power and/or long-haul transport. First approach was theoretical study, data collection and comparison of all potential alternatives. After considering all relevant criteria for this application, DME showed one of the best compromises between specific $NO_x$ and volumetric density, see Table 3. Based on that, the idea was to adapt a current state of the art Diesel HD transport engine to DME and find out what will be the main challenges. According to the literature the only area to be really adapted is the fuel injection system. Learning process with the fuel injection system HW and SW supplier is described in the next chapter.

| Fuel | C | H | O | H/C | LHV | dens | Mwt | mCO2 / mole fuel | BTE | sCO2 | sCO2 | delta | dens | delta |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [-] | [-] | [-] | [-] | [kJ/g] | [kg/m3] | [g/mol] | [g] | [-] | [g/kJ] | [g/kWh] | [%] | [MJ/m3] | [%] |
| Diesel FMF | 12.9 | 23.9 | 0 | 1.85 | 42.8 | 830.0 | 179.0 | 567.7 | 0.44 | 0.168392 | 606.2 | | 35524 | |
| CH4 | 1 | 4 | 0 | 4.00 | 55.0 | 193.7 | 16.0 | 44.0 | 0.44 | 0.11336 | 408.1 | -32.7 | 10655 | -70.0 |
| RON60 | 8 | 17 | 0 | 2.13 | 44.1 | 714.0 | 113.2 | 352.1 | 0.44 | 0.160259 | 576.9 | -4.8 | 31487 | -11.4 |
| Octane | 8 | 18 | 0 | 2.25 | 44.1 | 703.0 | 114.2 | 352.1 | 0.44 | 0.158844 | 571.8 | -5.7 | 31002 | -12.7 |
| Methanol | 1 | 4 | 1 | 4.00 | 22.7 | 792.0 | 32.0 | 44.0 | 0.44 | 0.137515 | 495.1 | -18.3 | 17978 | -49.4 |
| Ethanol | 2 | 6 | 1 | 3.00 | 29.7 | 789.0 | 46.1 | 88.0 | 0.44 | 0.146206 | 526.3 | -13.2 | 23433 | -34.0 |
| DME | 2 | 6 | 1 | 3.00 | 29.0 | 670.0 | 46.1 | 88.0 | 0.44 | 0.149735 | 539.0 | -11.1 | 19430 | -45.3 |

Table 3: Specific $CO_2$ production and volumetric densities for different fuels vs Diesel

## 3.2 DME production

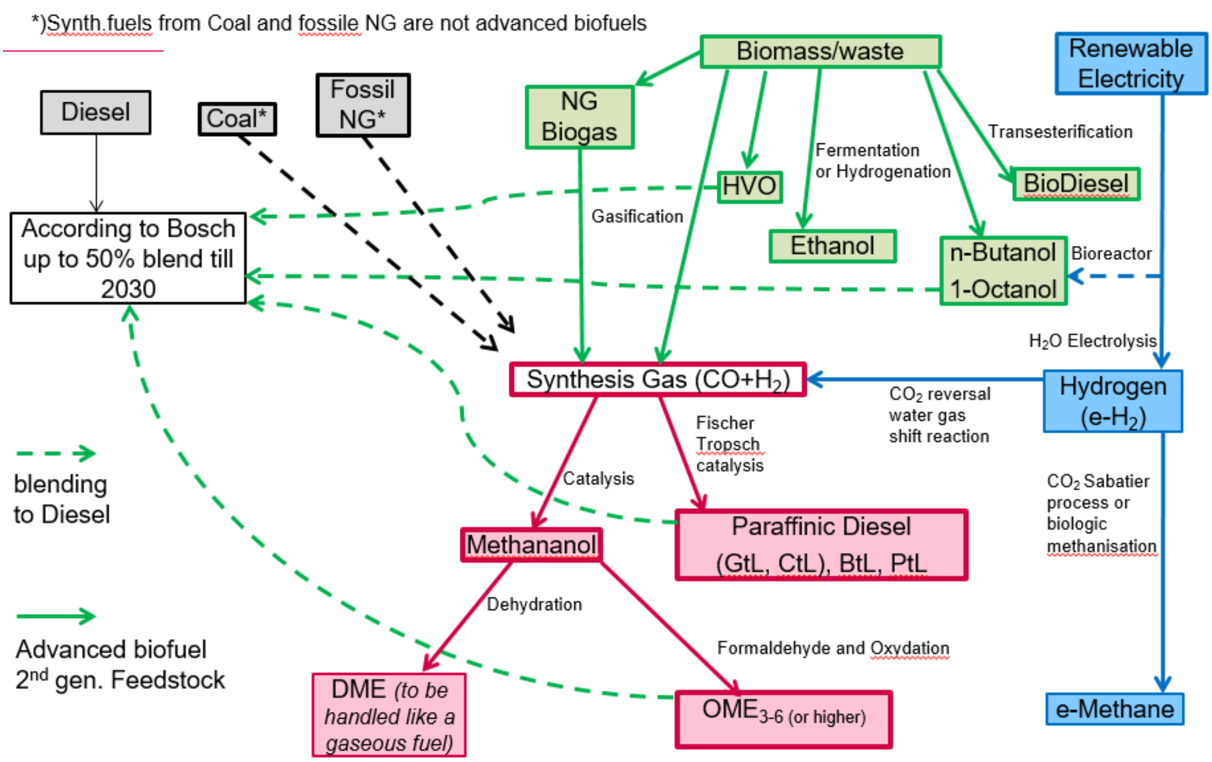



Figure 17: Feedstock and pathway overview about fuels for ICE (Internal combustion engines)

As shown in figure 17, DME can be produced from fossil feedstock (usually Natural Gas) or from Biomass (preferably waste material). Synthesis Gas can also be produced from renewable electricity.

| **Pathway description** | **Energy expended (MJ/MJ final fuel)** | **WTT GHG emitted (g $CO_2$eq/MJ final fuel)** |
|---|---|---|
| DME: NG 4000 km, EU prod., rail/road | 0.63 | 30.1 |
| DME: Rem prod., sea/ rail/road | 0.53 | 21.7 |
| DME: Rem prod. with CCS, Sea, Rail/Road | 0.54 | 11.7 |
| DME: Coal EU-mix, EU prod., rail/road | 0.94 | 126.2 |
| DME: from residual wood (truck, 500 km) | 1.26 | 10.6 |
| DME: from residual wood (truck, >500 km) | 1.29 | 12.7 |
| DME: from farmed wood (truck, 500 km) | 1.38 | 15.1 |
| DME: from farmed wood (truck, >500 km) | 1.4 | 17.2 |
| DME: W Wood via black liquor, road | 0.12 | 6.1 |
| DME: from renewable electricity, CO2 from flue gas | 1.39 | 1.8 |

Table 4: Overview about the $CO_2$ equivalent emissions of the different pathways
Source: extracted from Excel file CONCAVE "WTT_v5_results_Final_07062019"

The green highlighted pathways in Table 4 shows the renewable ones where at the end tail pipe emissions can be considered as zero once there is a standard and legislation defined. All of them have a significantly higher energy demand but very low GHG emissions during the WtT process. Currently, DME from NG is still the main production process worldwide and is carried out over solid acid catalysts (see next page).

There are two ways to produce DME from synthesis gas as shown in figure 18

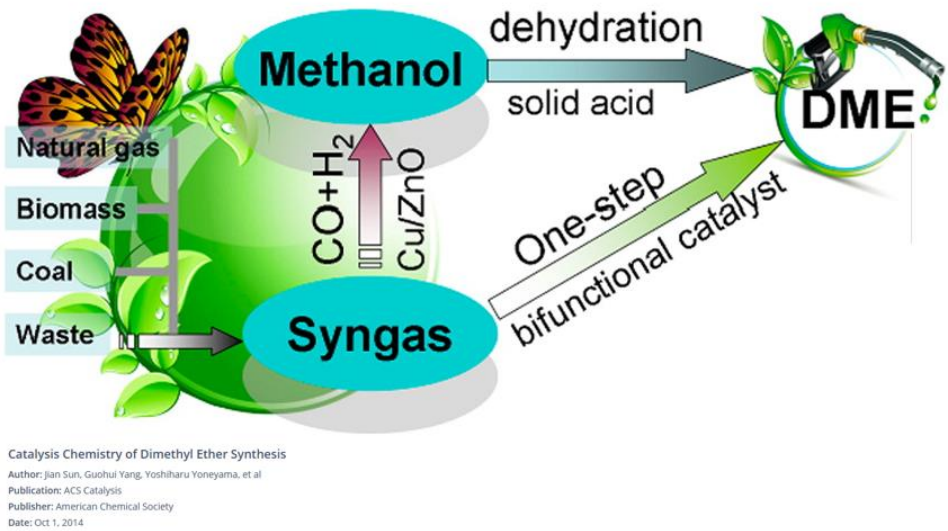



Figure 18: Two alternative ways to produce DME from synthesis gas
Source: American Chemical Society (October 1st 2014)

a) **Two-step process**: from biomass (such as Biogas, high solid waste or landfill) Syngas to Methanol and then dehydration to DME (Figure 19). In the first step, methanol production from syngas is catalysed over $CuO/ZnO/Al_2O_3$ at 50-100 bar and 270° C. In a second step, methanol is dehydrated in the presence of a zeolite acid or Lewis acid catalyst such as $Al_2O_3$, which have high selectivity and activity. These processes usually take place in a temperature range between 200 and 450° C and can reach pressures up to 18 bars. Companies that are offering production technology based on this two-step process are Haldor Topsøe, Lurgi, Mitsubishi Gas Chemical, Toyo Engineering Corporation and Uhde. The process to generate DME greatly depends on the quality of the syngas produced from a feedstock, such as NG, coal, residual oil, crude oil, biomass or wastes, and the use of the last two essential for achieving circular economy and sustainability. This syngas can be obtained from different technologies (methane reforming, gasification and more recently solid oxide electrolyser cell, which has the potential to convert $CO_2$ to syngas) and sources, as already mentioned, which makes the DME fuel versatile in the aspect of feedstock.

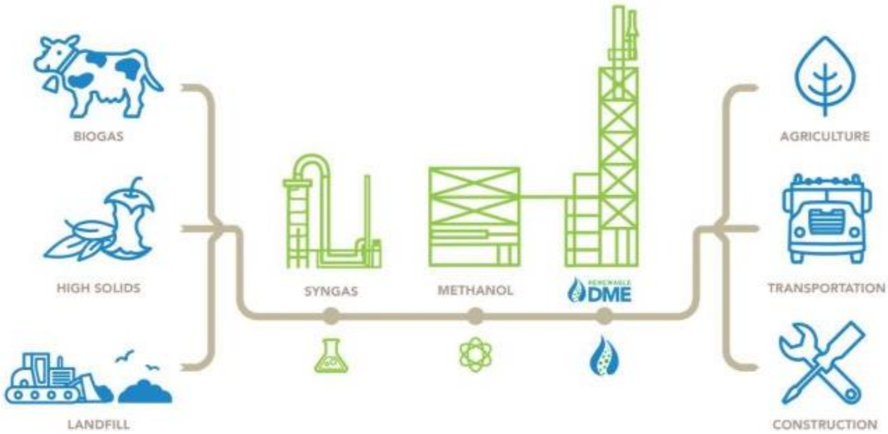



Figure 19: Oberon process for renewable DME (example of 2-step process)
Source: Oberon Fuels – DME in California (Elliot Hicks, COO Oberon Fuels)

Oberon Fuels, producer of clean-burning Dimethyl-Ether transportation fuel, has begun production of the first-ever rDME in the United States in 2021. It is the only current commercial production of this renewable molecule in the world. As part of a $6 million project funded by a grant from the California Energy Commission, Oberon is converting waste methanol into rDME at its upgraded facility in Brawley, California (see figure 19 above). It is the first time this feedstock has been used to make rDME at commercial scale. In addition to waste methanol, other potential feedstock includes: biogas from dairy waste, food wastes, agricultural waste as well as excess electricity and $CO_2$ resulting in ultra-low carbon to carbon-negative DME.

b) One-step process from Syngas to DME by bi-functional catalysts (bottom right on figure 18). Examples of Companies investigating this type: JFE (Japan Future Enterprise), KOGAS (Korea), Air Products&Chemicals (US) and Haldor Topsøe. Their proposed process solutions have been tested on a pilot and demo scale, but not yet been implemented on an industrial scale (state end of December 2020).

This description about DME production represents Well-to-Tank where the $CO_2$ contribution of the production and supply process is not yet standardized. The Onroad EU legislation cares about Tank-to-Wheel only. Figure 20 gives an overview about TtW $CO_2$ equivalent emissions for a long-haul truck (in EU typically a 40 tons tractor-semitrailer). It shows that under this aspect DME is one of the most promising one.

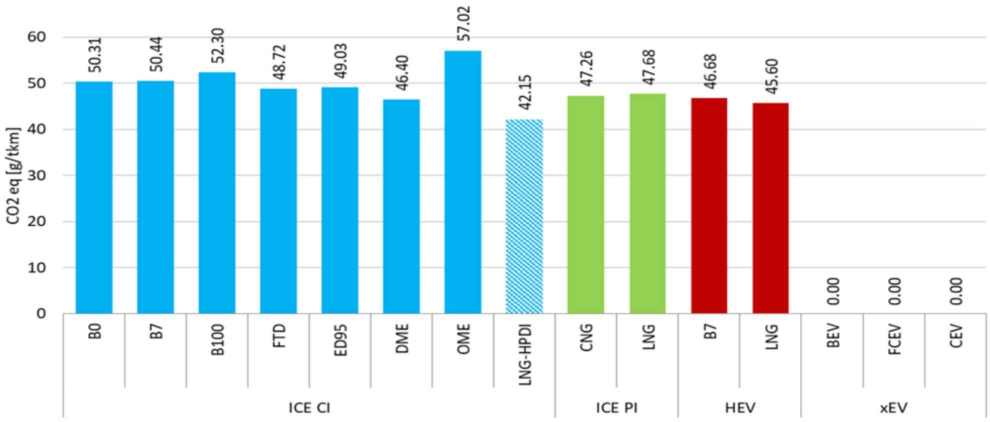



Figure 20: Summary of results for $CO_2$ equivalent emissions for all 2025 propulsion configurations of the group 5 tractor-semitrailer combination
Source: JEC Tank-To-Wheels report v5: Heavy duty vehicles (EU Commission, Concave, eucar)

## 3.3 Measurement concept

The experimental facility is described in section 2.1 and Figure 21 shows a panoramic view of the test bench setup. The basic principle is that the internal combustion engine is directly coupled to an asynchronous electric motor/generator which controls the engine speed. The engine load is controlled via the test bench automation system which demands a certain torque from the engine control unit. This setup is used for steady-state as well as for transient engine operation.

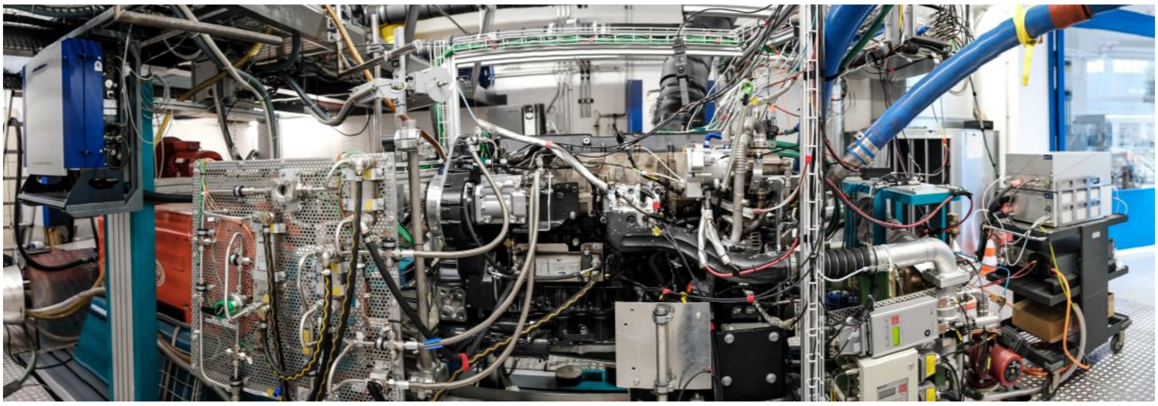


Figure 21: Engine (center), heavily equipped with sensors, connected to the dynamometer (left)

The following state-of-the-art measurement and control devices are used in the experimental setup:

- Test bench Horiba Dynas3 HD600 (peak power / torque capability of 600 kW / 400 Nm), torque measurement flange HBM T12 of highest precision class 0.03%.
- Automation System SRH STARS, including measurement box for temperatures (PT100 and thermocouples), pressures (equipped with Keller pressure transducers).
- Combustion air humidity measurement system (Vaisala).
- Combustion air flow measurement system (ABB Sensyflow P).
- Certification-grade exhaust gas emission bench (Horiba Mexa 7500DEGR). One line is used for engine-out emission measurement, the second line for emission measurement after exhaust gas after treatment. An EGR ($CO_2$ only) line is used to measure the $CO_2$ content in

the intake manifold which is needed to quantify the amount of external exhaust gas recirculation. The measurement principles are:

- Flame ionization detector (FID) for total hydrocarbons
- Non-dispersive infrared detector (NDIR) for CO and $CO_2$
- Chemiluminescence detector (CLD) for NO and $NO_2$
- Magnetopneumatic detector (MPD) for $O_2$

- Research-grade fourier-transform-infrared-spectrometer (FTIR) for the detection of a wide variety of species (Gasmet FTIR), special calibration for DME. The FTIR device is mainly used to measure for HCNO (Cyanic Acid) and $CH_2O$ (Formaldehyde) and it can be placed either up- or downstream of the exhaust gas after treatment system.
- Continuous soot mass concentration measurement (AVL Micro Soot Sensor).
- High-precision tailpipe ammonia detection device (laser diode spectrometer Siemens LDS).
- DME flow measurement system (dual-Coriolis sensors); the fuel consumption is continuously measured and cross-checked with the emission data (carbon balance method).
- Cylinder pressure indication (Kistler piezoelectric sensor in the cylinder, piezoresistive sensors in intake/exhaust channels).

All measurement data is recorded on the test bench automation system with the required temporal resolution. Crank-angle-resolved data in the test bench indication system is recorded by Kibox from Kistler with the Kibox Cockpit Software. The data is then subsequently used for evaluation. An FPT Software originally developed for TU Graz is used for this. The difference to common tools is the automatic adaptation of the pressure gradient in X- and Y-axis and calculation of the effective compression ratio to calculate the heat release rate.

## 3.4 Simulation as parallel activity to engine and infrastructure preparation

### 3.4.1 Politecnico Milano: DME engine simulations (mesh generation, turbulence and numerical models, spray models, combustion models and case setup)

**1st PoliMi simulation campaign: Diesel vs. DME comparison on two different operating condition**

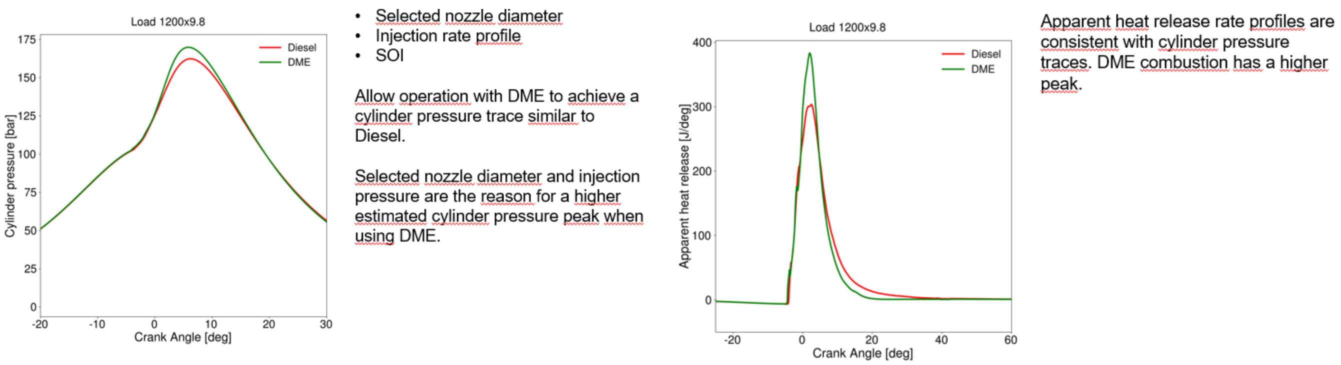
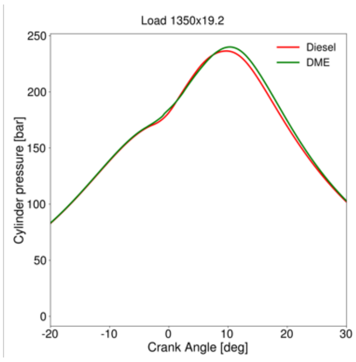
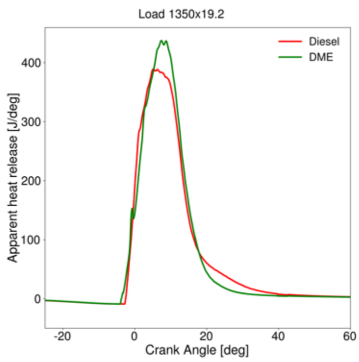



Figure 22a: Simulation results at 1200rpm / 9.8 bar




Even better matching of cylinder pressure for the higher load case between DME and Diesel operation




Some differences still exist in terms of apparent heat release rate

Figure 22b: Simulation results at 1350rpm / 19.2 bar

**Preliminary results of 1st PoliMi investigation**:

- Selected HW (injection pressure, nozzle size) allows to reach in principle similar performances compared to Diesel
- No advantage offered in terms of engine efficiency: need to operate on combustion modes
- Higher $NO_x$ emissions: need to increase EGR rate

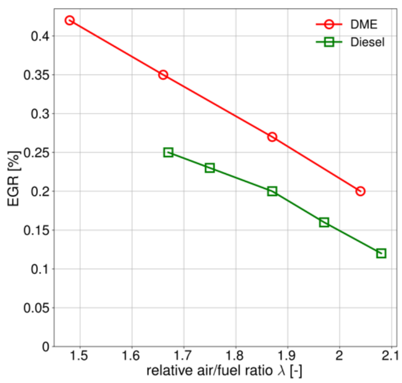
**2nd PoliMi simulation campaign: effects of EGR on performance and $NO_x$ emissions**

## Simulated operating points

- Same relative air fuel ratio $\lambda$
- Same fuel energy injected
- but to keep the same $\lambda$ it is necessary to use different EGR rates since DME is oxygenated.
- An additional operating point was tested using stoichiometric air/fuel ratio and without EGR. The initial conditions were changed by reducing the IVC pressure from 1.95 to 0.765 bar.

| DME | | | |
|---|---|---|---|
| 1200x9.8 | | | |
| Condition | $\lambda$ | EGR | SOI |
| 1 | 2.04 | 20.24% | -5.9 |
| 2 | 1.87 | 27.00% | -5.9 |
| 3 | 1.66 | 35% | -7 |
| 4 | 1.48 | 42% | -8.5 |
| S | 1.00 | 0% | -5.9 |

| Diesel | | | |
|---|---|---|---|
| 1200x9.8 | | | |
| Condition | $\lambda$ | EGR | SOI |
| 1 | 2.08 | 12% | -5.1 |
| 2 | 1.97 | 16% | -5.1 |
| 3 | 1.87 | 20% | -5.1 |
| 4 | 1.75 | 23% | -5.1 |
| 5 | 1.67 | 25% | -5.1 |




To keep the same relative air-fuel ratio, DME requires a higher EGR rate.

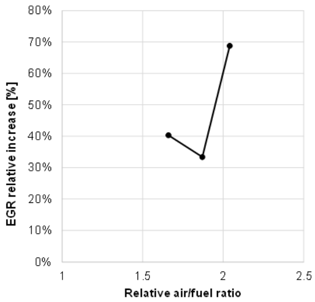
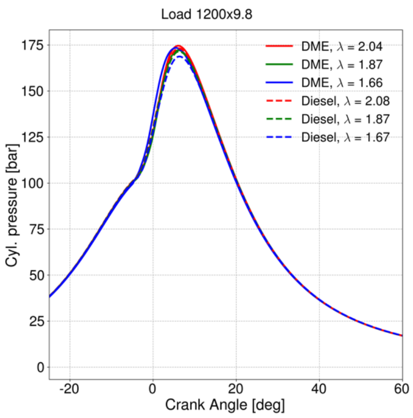
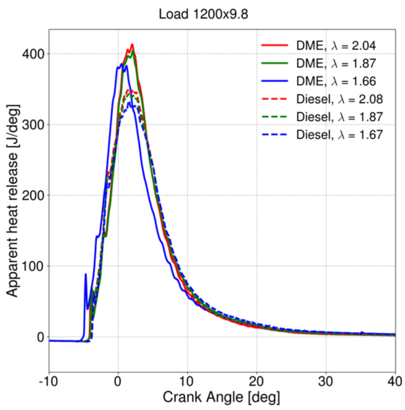



Figure 23: Simulation results at 1200rpm / 9.8 bar

Figure 24: rel.air/fuel ratio f (EGR rates)




Very similar cylinder pressure traces obtained when using Diesel and DME fuels.




Apparent heat release is different because of the combination between injection pressure and nozzle size.

DME seems to have a higher air-entrainment, probably enhanced by the fact that the fuel is already oxygenated.

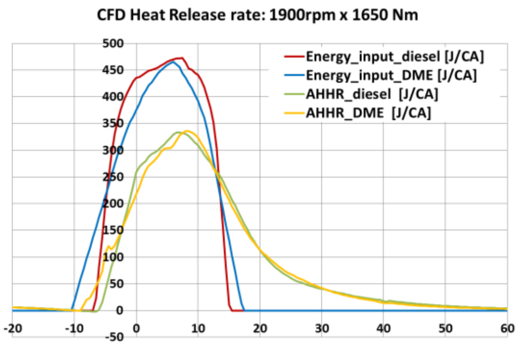
Figure 25: Sim. Cyl. Pressure Diesel vs.DME

Figure 26: Sim. AHRR Diesel vs.DME

**Preliminary results of 2nd PoliMi investigation (Operation with Diesel and DME at 1200x9.8 condition. Combined variation of EGR and relative air/fuel ratio**:

- Increase of EGR is necessary to keep the same relative air/fuel ratio with DME
- Under lean operation DME achieves the same performance and efficiency like Diesel
- $NO_x$ reduction with DME is possible (or same level of $NO_x$ with reduced EGR rate compared to Diesel)

### 3.4.2 DME simulation results at rated power: DME nozzle dimensioning using 3D CFD combustion



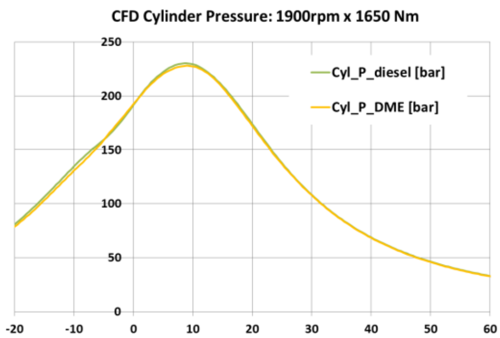




Figure 27: CFD heat release rate Diesel vs. DME

Figure 28: CFD Cyl. Pressure Diesel vs. DME

- Similar Cylinder Pressure for DME and Diesel Combustion (@ same $BSNO_x$
- engine out) if injection duration is adjusted by selecting suitable nozzle hole diameter.
- pRail diesel = 2000 bar / Dinj = 23°CA vs pRail DME = 1100 bar / Dinj = 28°CA
- Indicated Thermal efficiency gain with DME: +1%
- CO emissions with DME reduced by a factor 20 and no Soot

# 4 Results and discussion

## 4.1 Experimental Diesel vs DME emissions and performances comparison for two load points

Figure 29 shows the measured brake specific $CO_2$ in function of the brake specific NOx emissions at engine out for the typical Cruise load point (1200rpm/ ≅100 kW) and the best brake thermal efficiency load point (1350rpm/75%). A minimum 11% reduction of $CO_2$ TtW emissions is expected with DME vs Diesel for a similar thermal efficiency due to the more favourable H/C ratio of the DME fuel. The more sustainable the DME source and production process (GHG emissions WtT), the higher the difference compared to Diesel.

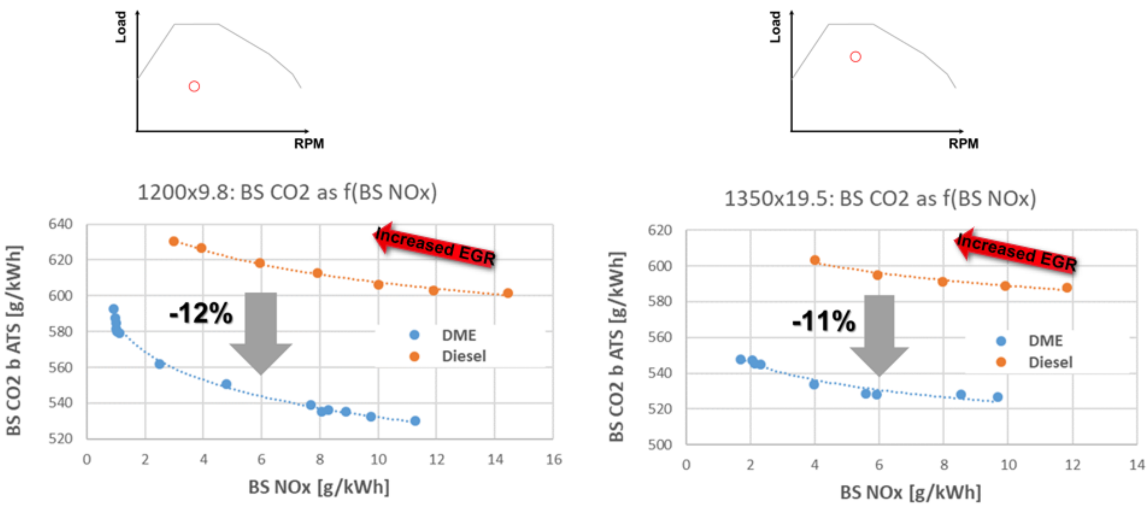



Figure 29: specific engine out $CO_2$ emissions in function of specific NOx after engine for two load points

As shown in Figure 30, the BTE can be improved at part load by nearly 1% point and slightly better at higher load. BS NOx down to 1g/kWh is achievable while maintaining a BTE above 40%.

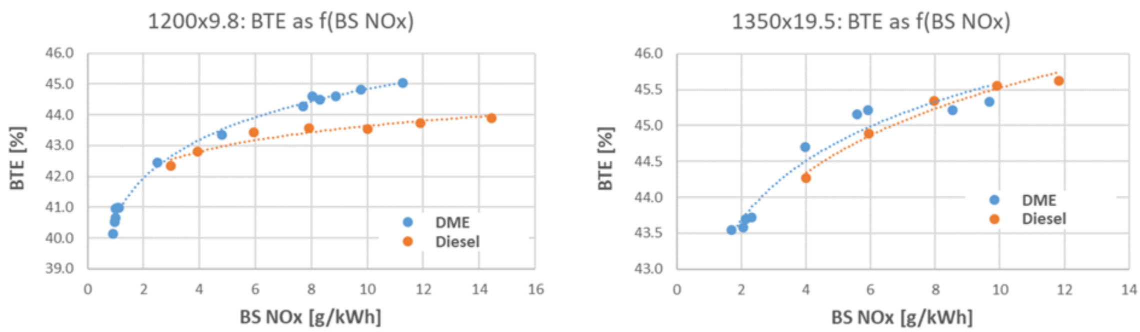



Figure 30: Brake Thermal Efficiency in function of specific NOx after engine for two load points

Regarding soot, DME has the big advantage over Diesel that the fuel molecule contains oxygen and no carbon double-bounds. Additionally, the good spray behavior (fast breakup/evaporation) leads to the situation that zones with lack of oxidant are almost non-existent [7][8]. The soot concentration was measured with an AVL micro soot sensor. No Soot was ever detected even for high level of EGR as seen in Figure 31. Soot is a major limiting factor with diesel fuel if BS NOx has to be brought below 4g/kWh on a heavy-duty Diesel engine.

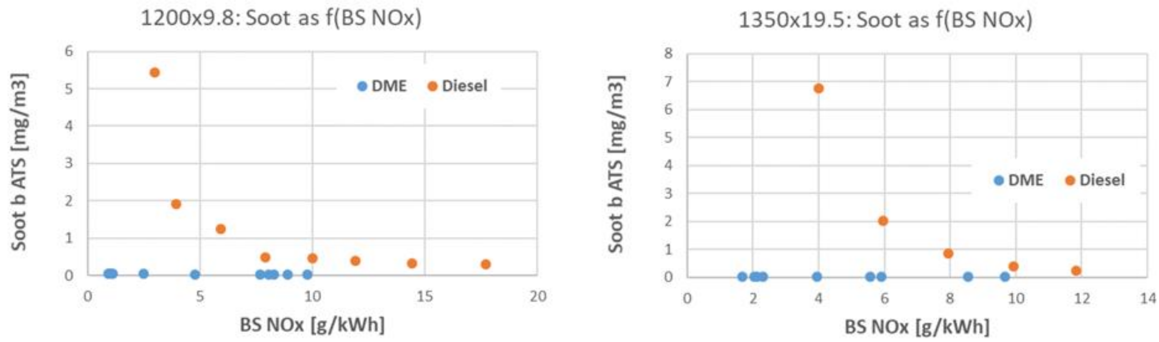



Figure 31: Soot emissions in function of specific NOx after engine for two load points

Figure 32 is showing that for a target BS NOx engine out, less EGR is required with DME because late injection and low injection pressure tuning strategies are possible as soot production is no more a limiting factor.

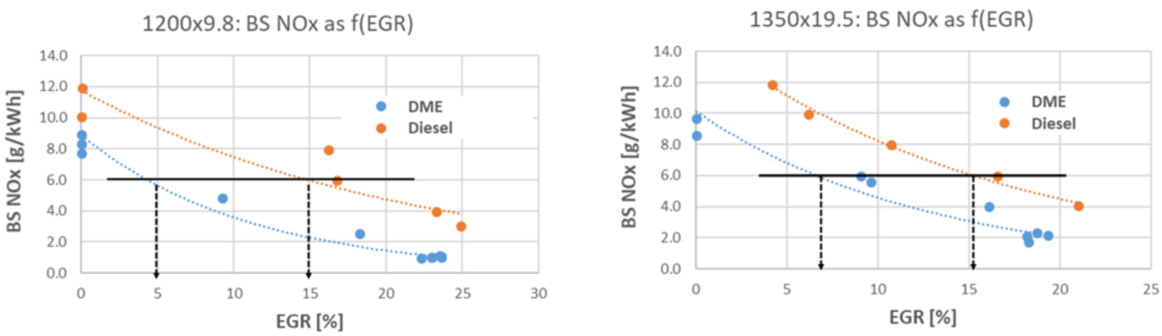



Figure 32: specific NOx emissions after engine in function of EGR for two load points

Brake specific THC concentration with DME is about 1/5 of Diesel, which confirms a good combustion chamber set up as seen in Figure 33. HC emissions from DME are not affected by the level of EGR. These results are in contrast with literature results where some DME engines showed often high levels of THC emissions [9]. In our case, the proper design of the combustion chamber and the injection system led obviously to a very good situation regarding THC emissions.

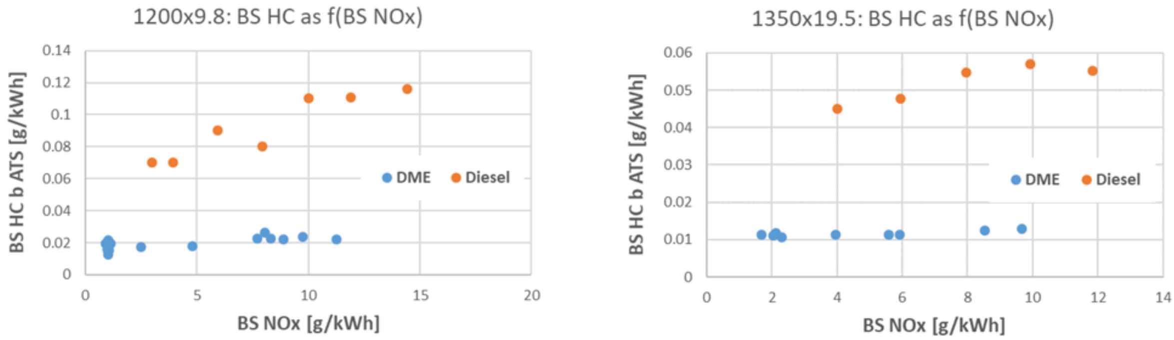



Figure 33: specific HC emissions in function of specific NOx after engine for two load points

Brake specific CO concentration just after the engine with DME is very similar to Diesel as shown in Figure 34. The level of CO remains quite low for EGR level below 20%.

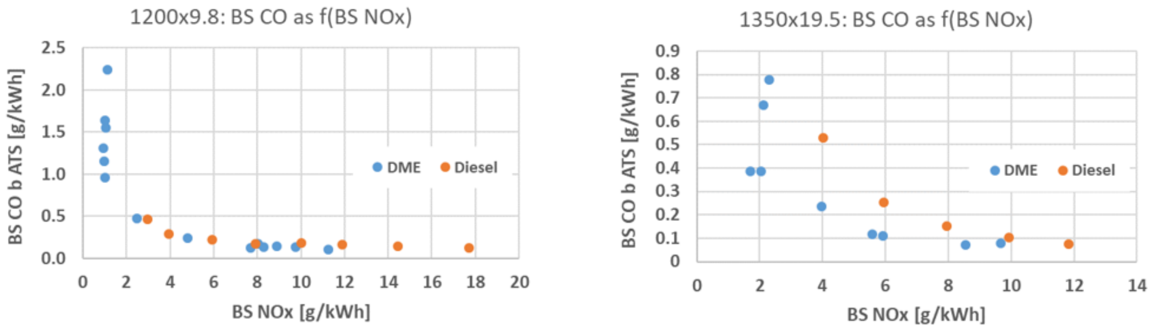



Figure 34: specific CO emissions in function of specific NOx after engine for two load points

## 4.2 FTIR measurements

FTIR spectrometer measurements were conducted in order to confirm preliminary results for low THC and CO emissions. In addition, DME, HCNO (Cyanic Acid) and $CH_2O$ (Formaldehyde) were also analyzed to understand the effect of an oxygenated fuel like DME on potential harmful chemical species. In Figure 35, we can see the region in the engine map were FTIR measurements were carried out, including different level of EGR, as well as a comparison of NOx measurements between the certification-grade standard emission analyzer (Horiba Mexa 7500 which samples the engine's raw emissions) and the FTIR spectrometer, confirming a good correlation between both methods.

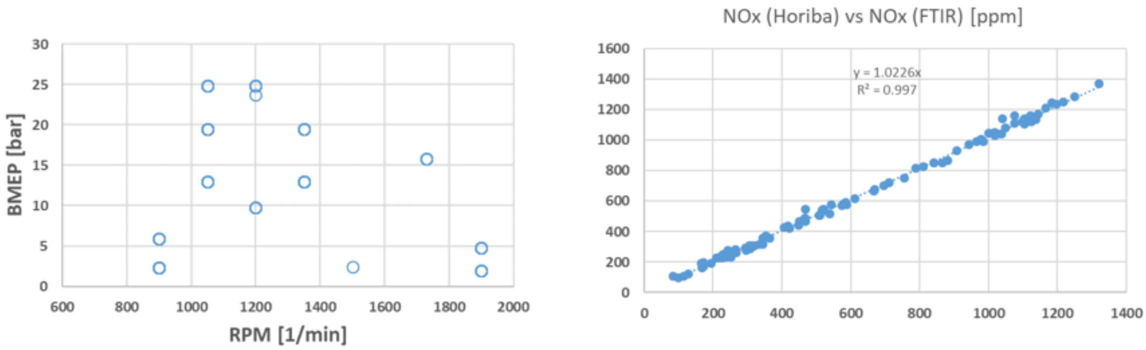



Figure 35: FTIR measurements in the engine map and comparison of NOx measurements

CO and HC emissions were confirmed with two different measurement methods as seen Figure 36: CO emissions with NDIR & FTIR and HC emissions with FID & FTIR. Regarding the HC emissions measurement discrepancies exist between FID and FTIR methods, it can be explained by the following: FID analyzers are known to capture most hydrocarbons very well (response factor around 1) and therefore well-known and accepted for analyzing exhaust HC emissions using conventional fossil fuels. However, they are less reliable to capture oxygenated compounds like Aldehydes, Ethers and Alcohols correctly (e.g. almost no response to Formaldehyde) and/or show higher variations in response factors. The response factor of the FID from the Mexa 7500 to DME was tested and found to be around 0.6 on the test bed. Therefore, assuming most of the detected HC being DME a correction factor (=1/0.6) was applied on the FID HC measurements to represent an upper bound. On the other hand, the FTIR method is able to detect simultaneously a high number of different components by analyzing spectral emissions. Typically, automotive FTIR spectrometers are calibrated for Alcohols, Acids and Aldehydes. However, a DME-dedicated spectral emission evaluation method has been implemented by the device manufacturer (Gasmet) for this project so that precise measurements could been performed.

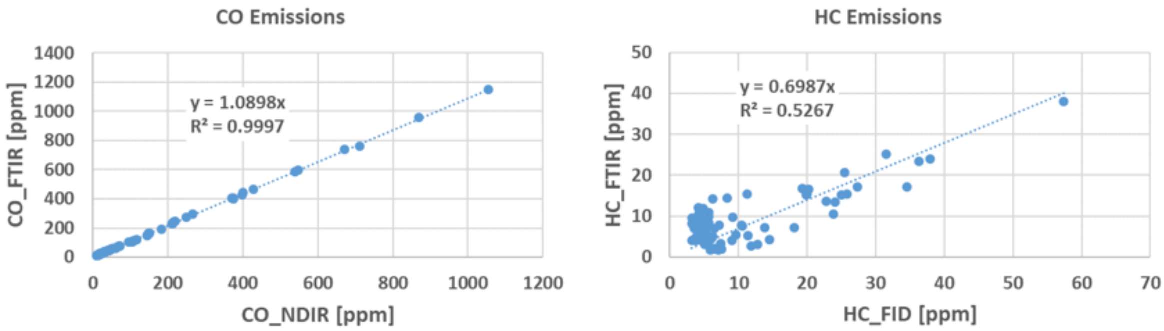



Figure 36: CO and HC measurement method comparison.

Figure 37 shows that DME emissions can represent maximum 1/3 of the HC total emissions but only at high speed with 10% load when combustion temperatures are low, resulting in some amount of DME being not oxidized. Formaldehyde ($CH_2O$) represents only a couple of ppm.

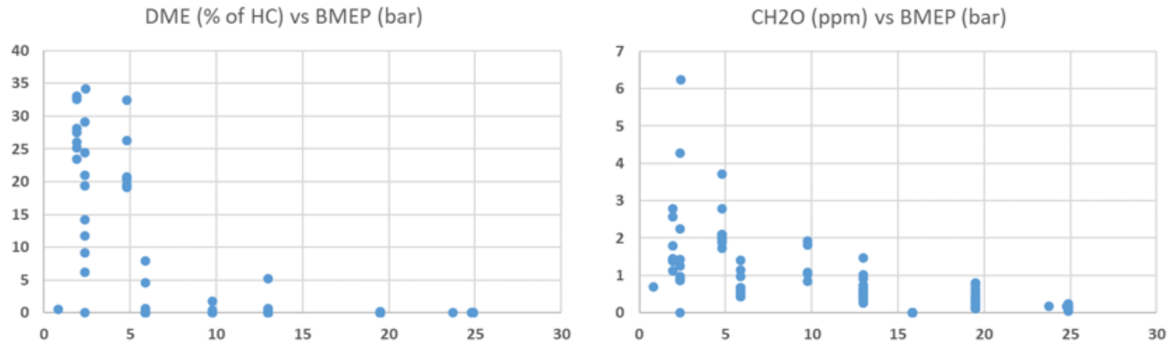



Figure 37: DME and $CH_2O$ measurement in function of BMEP

In Figure 39a, we can see HCNO and $N_2O$ emissions in function of BMEP. $N_2O$ is a powerful GHG (factor ~300 to $CO_2$) and its engine-out emission are neglectable (right diagram).

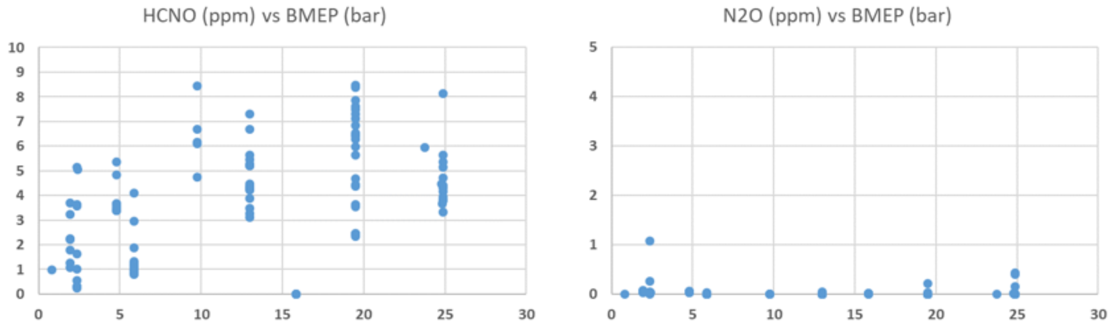



Figure 39a: HCNO and $N_2O$ measurement in function of BMEP

In Figure 39b, we can see $CH_4$ emissions in function of BMEP. Methane is also a powerful GHG but far less than $N_2O$ (factor ~25). As the diagram below is showing, the emissions are neglectable.

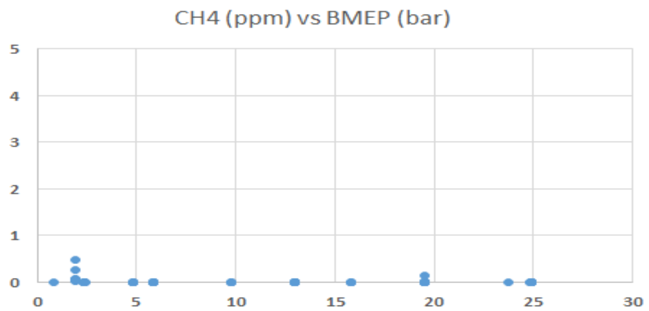



Figure 39b: $CH_4$ measurement in function of BMEP

Also during a WHTC the methane emissions engine out as well as tail pipe are very low as Figure 39c is pointing out. In any case, the CH4 emissions are always included in the declared THC emissions. Slightly higher values can be seen in the transient phases but still on a very low level.

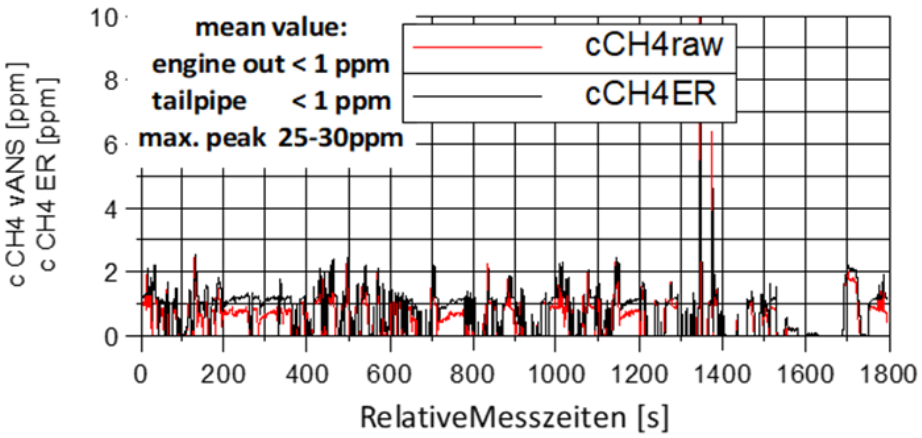



Figure 39c: $CH_4$ emissions during WHTC

### 4.3 Particle Number (PN) measurement

Figure 40 shows that specific particle number measured before ATS is below 3.0e10/kWh which is well under the EU6 emission level of 6.0e11/kWh. PN is almost two orders of magnitude lower than what the emission standards required.

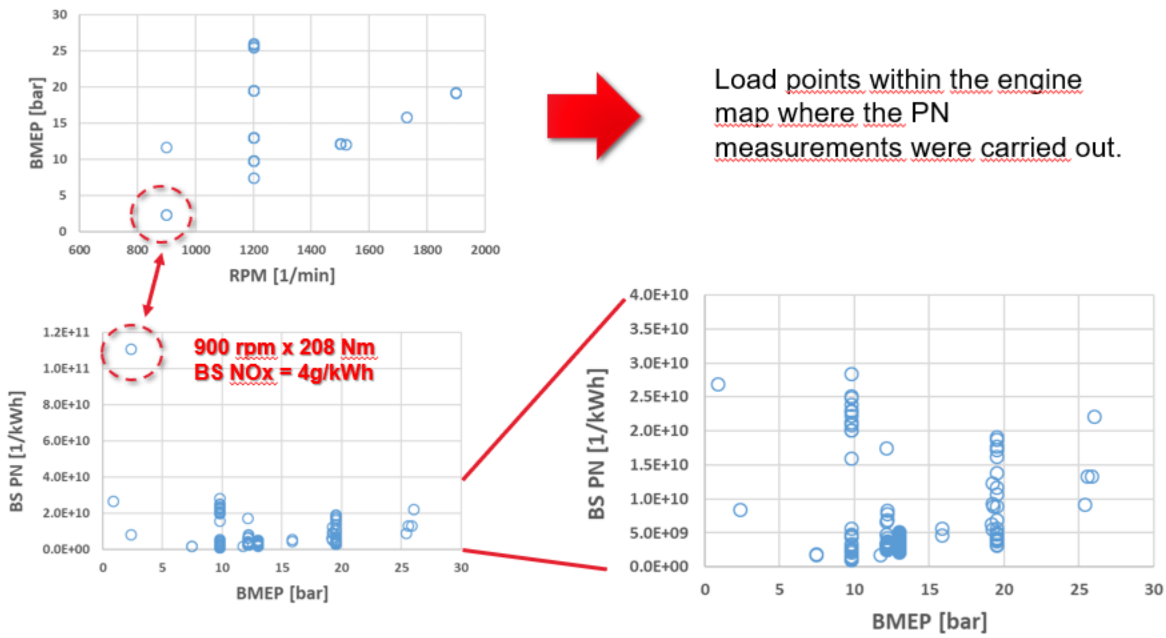



Figure 40: Particle Number measurements

## 4.4 Diesel vs DME: HRR comparison of three load points for a BS NOx = 8g/kWh

The following charts will show some comparisons of Heat Release Rates between diesel and DME for three load points which have the same specific NOx engine out at 8g/kWh.

Figure 41 shows that the end tail of the heat release rate with DME fuel is much faster which benefits directly the thermal efficiency. Both load points are running with the same Boost pressure which gives a higher air fuel ratio lambda with DME fuel and therefore further improves the thermal efficiency. The Rail pressure with DME is about half that with diesel fuel leading to a longer injection duration with DME but the engine still manages a 1% improvement in BTE. With DME, we can see a very smooth HRR, almost a bell like shape.

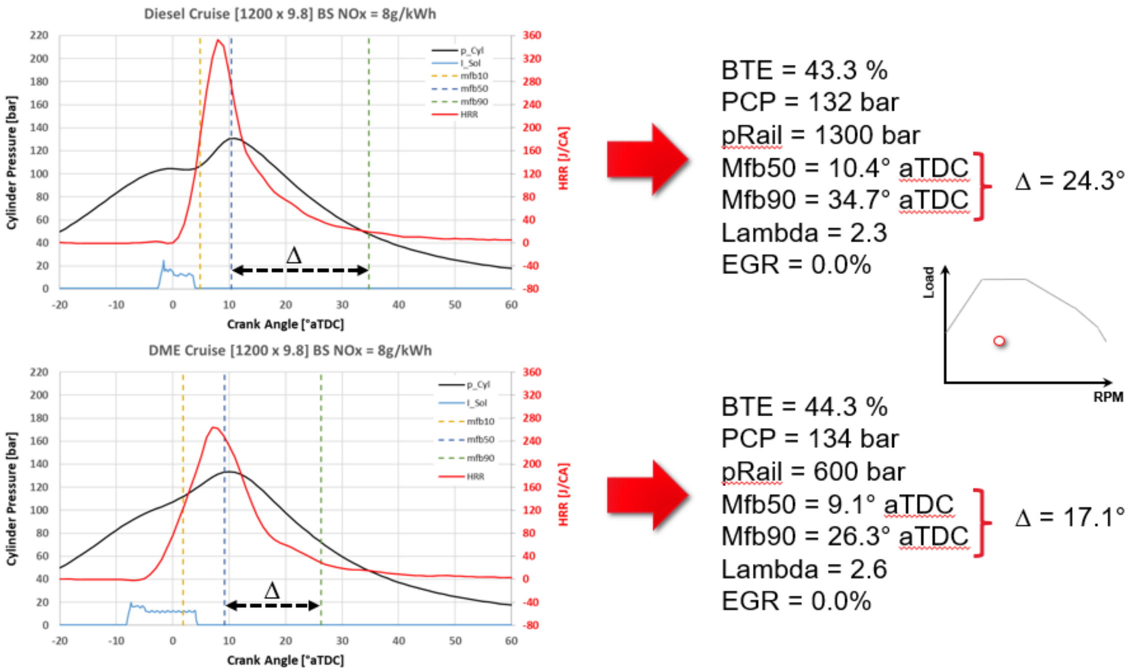



Figure 41: Comparison of Cylinder pressure, Heat Release Rate and combustion metrics between Diesel and DME fuels for the Cruise load.

Figure 42 shows for the maximum Torque load that the end tail of the heat release rate with DME fuel is faster. Here the DME load point is running with a lower Boost pressure to keep the air fuel ratio lambda identical between diesel and DME. For high load points, there is no improvements of running with DME in terms of thermal efficiency.

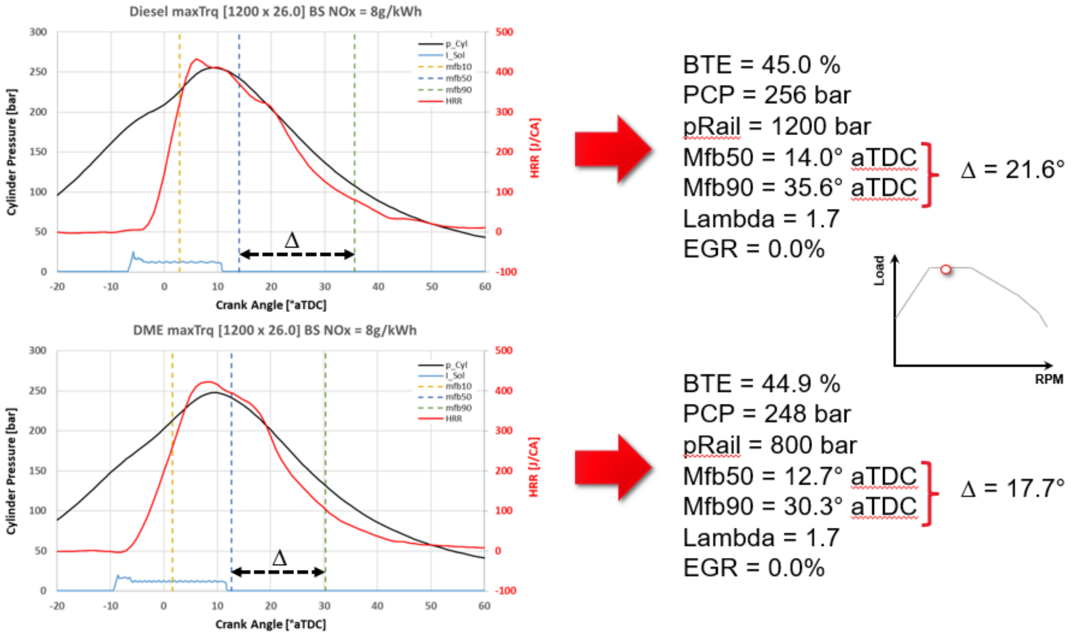



Figure 42: Comparison of Cylinder pressure, Heat Release Rate and combustion metrics between Diesel and DME fuels for the Maximum Torque load.

Figure 43 shows for the best BSFC load that the end tail of the heat release rate with DME fuel is again faster. For the diesel load point, 10% EGR was required to keep the ATS at 8g/kWh as high rail pressure was used. We can see that the Peak Cylinder Pressure is close to 250 bar with diesel whereas with DME, a very similar thermal efficiency is achieved without EGR and lower Peak Cylinder Pressure. The Boost pressure used for the two fuels were similar.

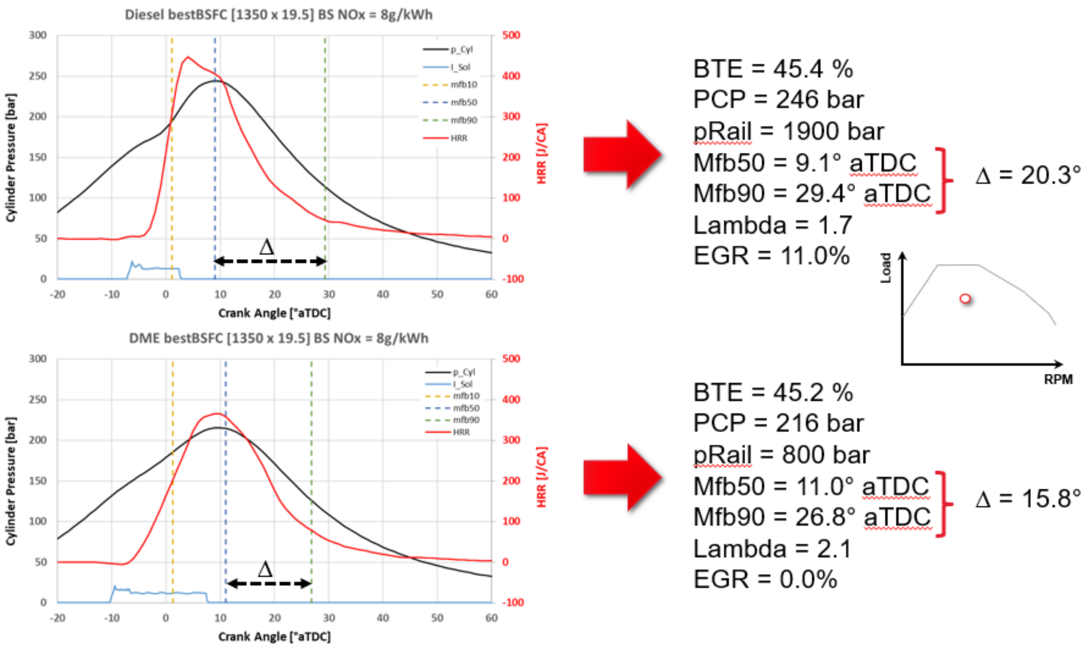



Figure 43: Comparison of Cylinder pressure, Heat Release Rate and combustion metrics between Diesel and DME fuels for the best BSFC load.

The starting gradient of the heat release rate with DME is much smoother than with diesel. This can be explained by the fact that 1) DME has a higher Cetane Number and the air-fuel mixture preparation within the DME spray is quite fast leading to a quasi-non-existent premixed phase 2) the energy rate input with DME is lower because of the longer injection duration to compensate the lower energy density of DME.

## 4.5 Diesel vs DME: HRR comparison for one load points for a BS NOx = 4g/kWh

Figure 44 shows for the 75% load at 1200 rpm a comparison of HRR between diesel and DME for a lower specific NOx engine out at 4g/kWh. With DME, a similar thermal efficiency was achieved with 10% EGR, a limited Rail pressure and late injection. Even with a late mfb50, the end tail of the heat release is fast.

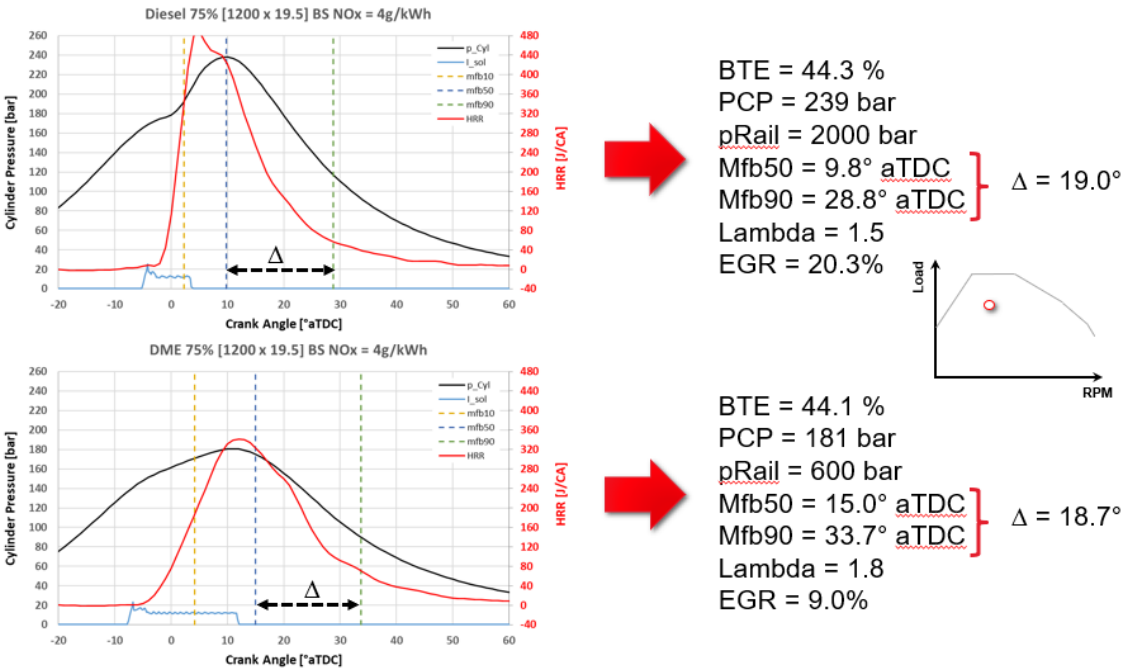



Figure 44: Comparison of Cylinder pressure, Heat Release Rate and combustion metrics between Diesel and DME fuels for 75% load at 1200 rpm.

## 4.6 DME: HRR for one load points for a BS NOx = 0.5g/kWh

Figure 45 shows for the 29% load at 1200 rpm, the HRR with DME for a very lower specific NOx engine out at 0.5g/kWh. With DME, Euro6 emission level can be achieved at part load with roughly 35% EGR. The thermal efficiency achieved is still good at about 39%. Such load could be applied during engine warm up before the ATS SCR is turned on. Regarding CO emissions for such high level of EGR: specific CO reaches 3.8g/kWh or 1000 ppm but exhaust gas temperature before ATS is 270°C, therefore the DOC should be able to oxidize the CO.

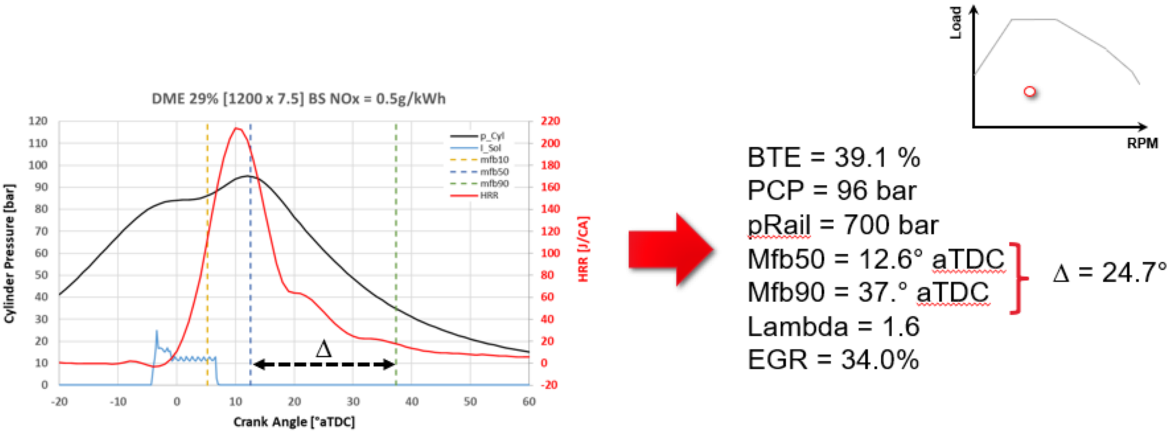



Figure 45: Cylinder pressure, Heat Release Rate and combustion metrics for DME fuels for 29% load at 1200 rpm with BS NOx = 0.5 g/kWh

### 4.7 DoE for optimum calibration

An extensive DoE, covering most of the key points in the engine map (see Figure 46), for the rail pressure, start of injection and boost pressure was performed in order to find the best compromise between brake thermal efficiency, NOx / CO / HC emissions, Peak Cylinder Pressure and exhaust gas temperature for two different configurations: 1) engine is running without external EGR 2) the BS NOx engine out is always kept at 4g/kWh by controlling the EGR with the pump.

Regarding the Boost pressure, it was found out that the base map of the diesel engine configuration can be used as it is quite close to be optimum for the DME engine.

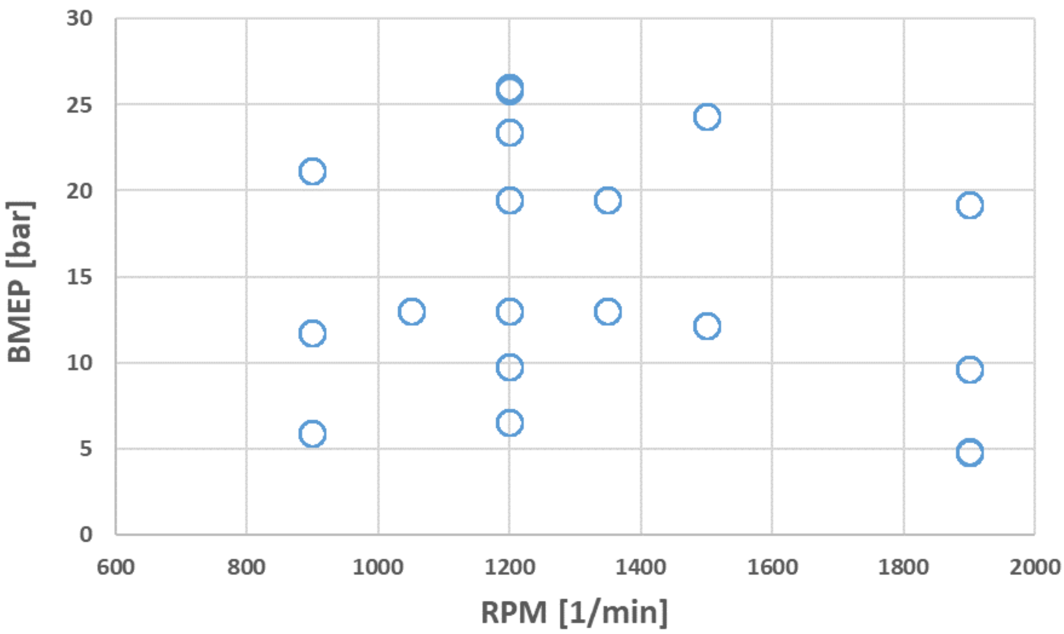



Figure 46: key points covered in the engine map for the DoE

In Figure 47 & 48, we can see the results of the DoE for: 1) the Cruise load point without EGR and 2) BS NOx = 4g/kWh. The Green dot represents the optimum point of the DoE and it will be used to develop later the calibration of a complete engine map.

A brake specific $CO_2$ of 540g/kWh can be achieved without EGR and 550g/kWh with a BS NOx = 4g/kWh. For info: an optimized diesel engine with low friction pack and down speed tuning has the potential to reach a brake specific $CO_2$ of about 600g/kWh

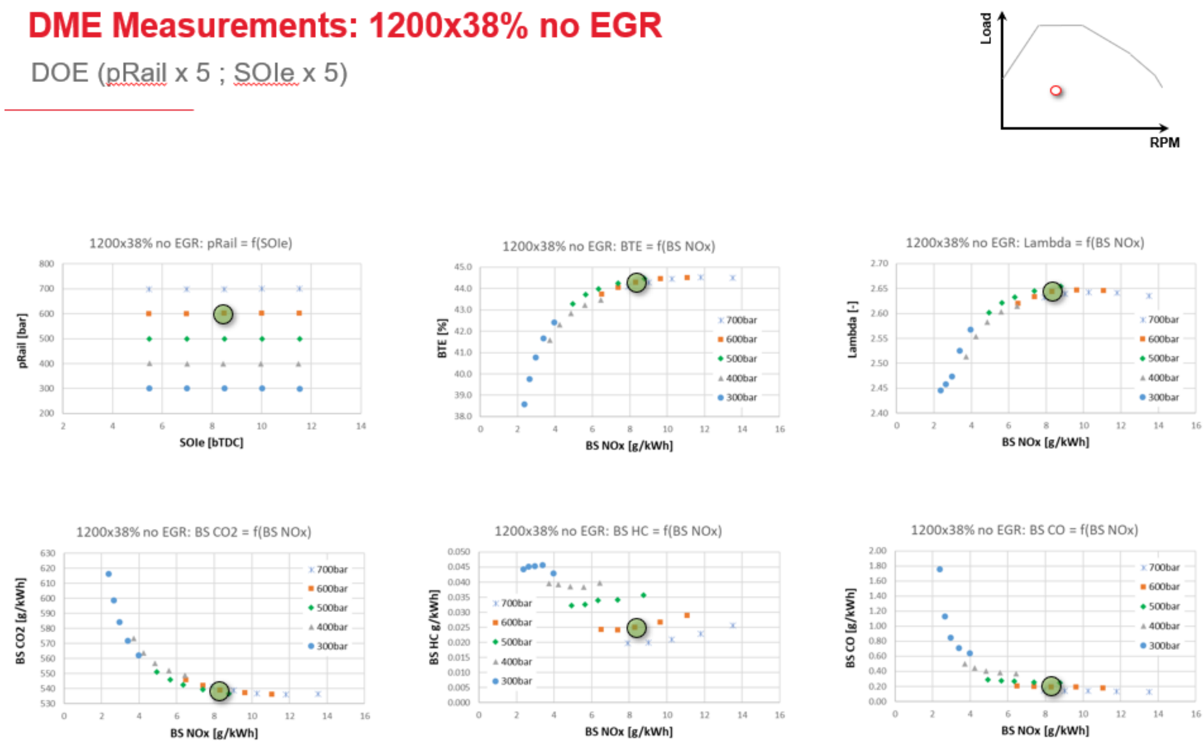



Figure 47: DoE results for the Cruise load point without EGR

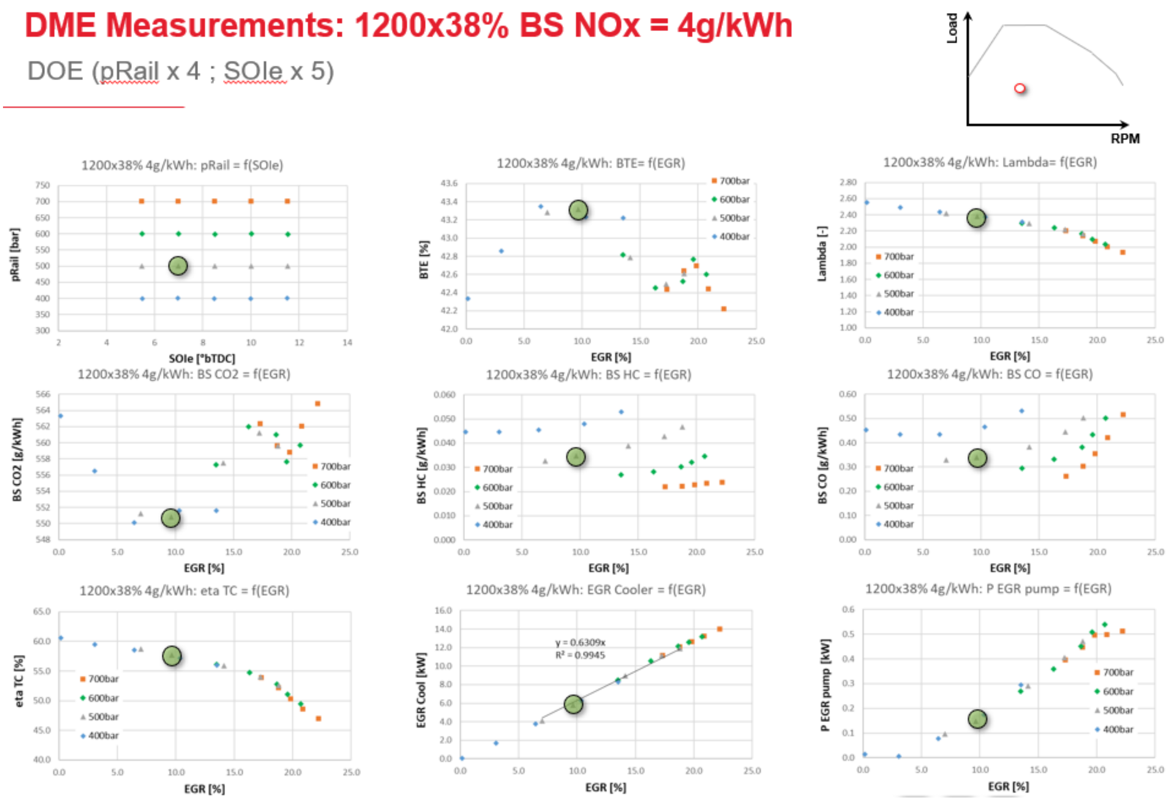



Figure 48: DoE results for the Cruise load point with BS NOx = 4g/kWh

In Figure 49, the Peak Cylinder Pressure and the exhaust gas temperature in both configurations are monitored to check the border limits. Here, for the cruise load point, the minimum temperature must be kept above 200°C to allow urea dosing when an ATS is connected to the engine.

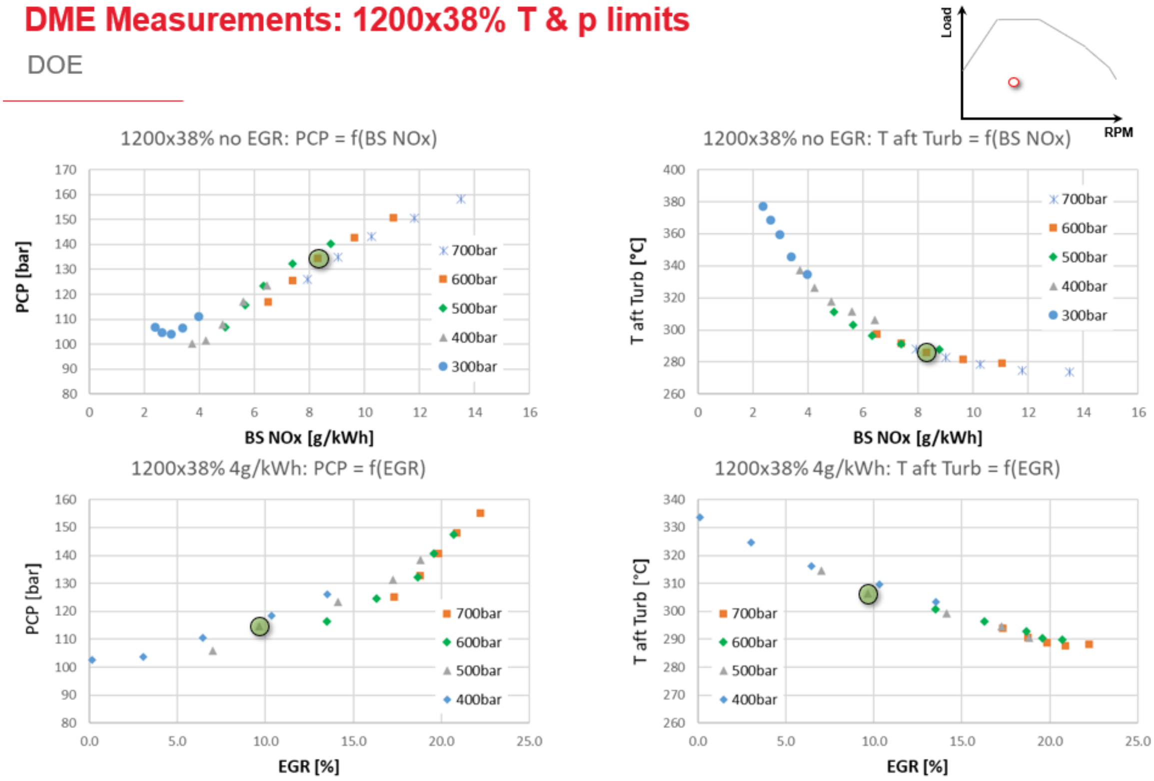



Figure 49: Peak Cylinder Pressure and Exhaust Gas Temperature resulting from the DoE results for the Cruise load points

In Figure 50 & 51, we can see the results of the DoE for the rated power load point without EGR and BS NOx = 4g/kWh. The Green dot represents the optimum point of the DoE.

A brake specific $CO_2$ of 580g/kWh can be achieved without EGR and 572g/kWh with a BS NOx = 4g/kWh. For info: an optimized diesel engine with low friction pack and down speed tuning has the potential to reach a brake specific $CO_2$ of about 570g/kWh but for a higher specific NOx emission level.

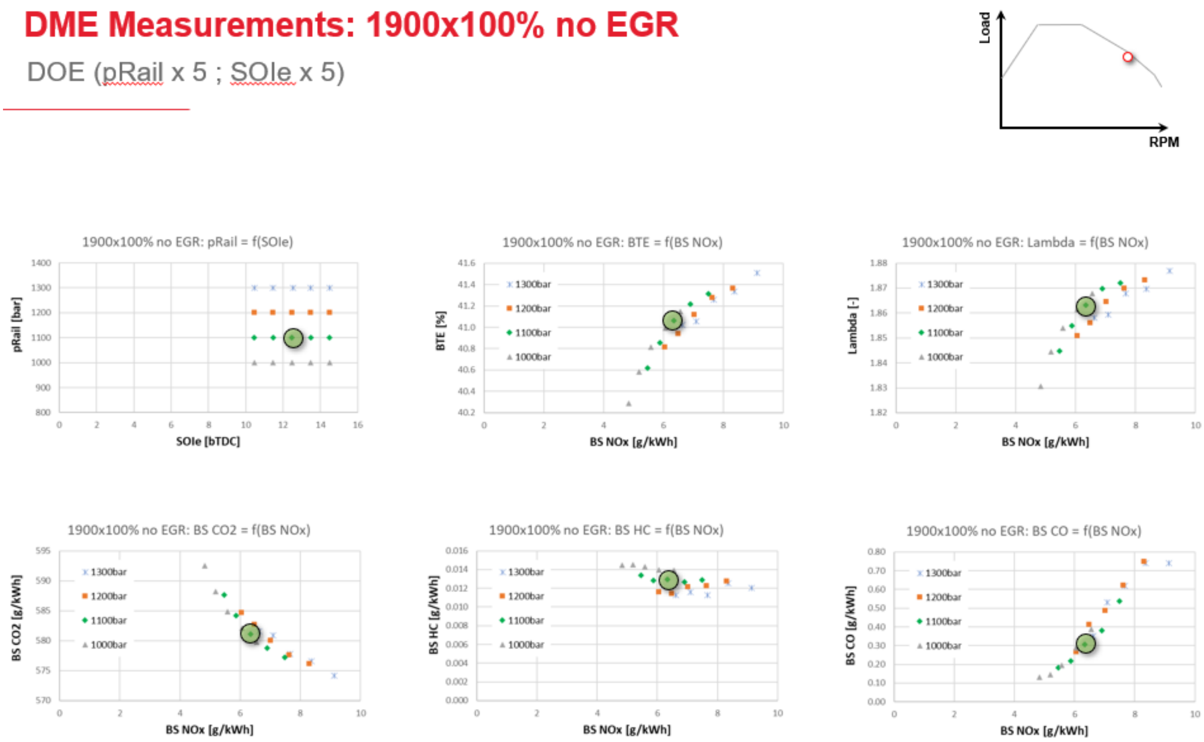



Figure 50: DoE results for the rated Power load point without EGR

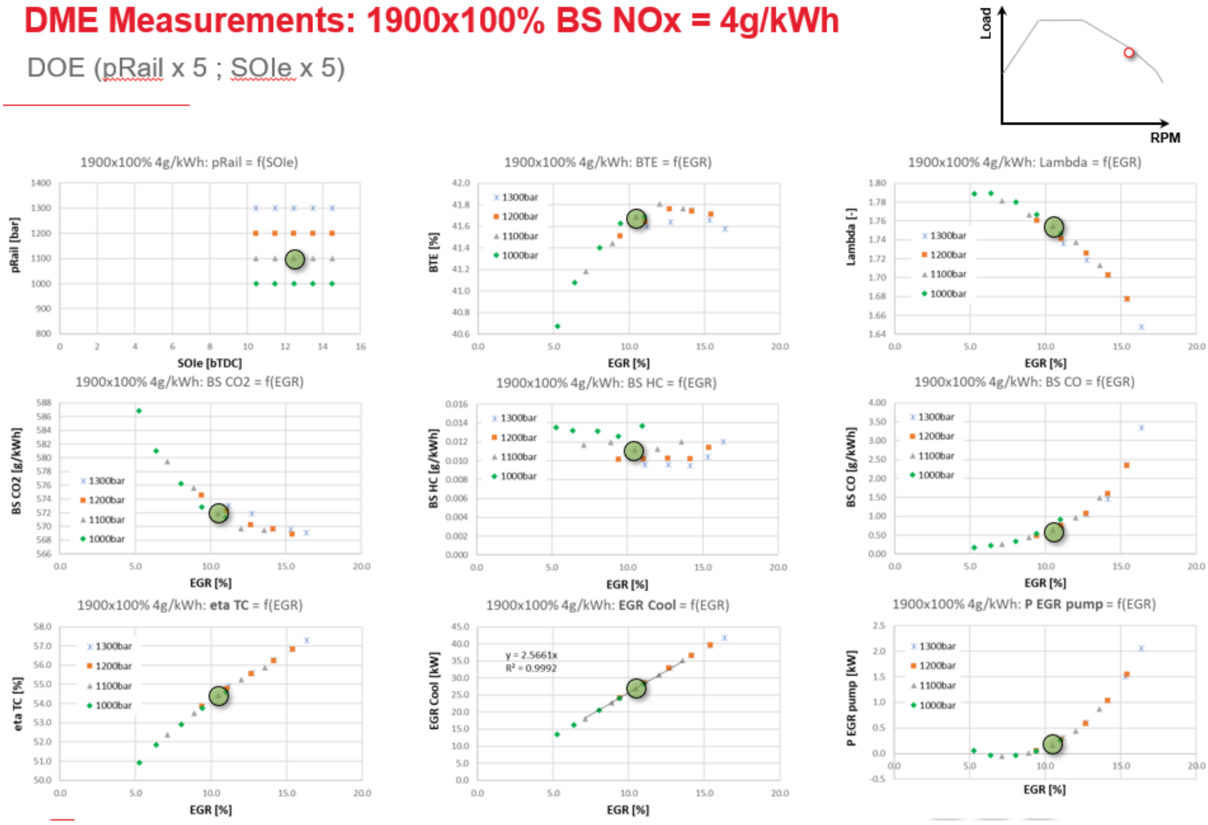



Figure 51: DoE results for the Rated Power load point with BS NOx = 4g/kWh

In Figure 52, the Peak Cylinder Pressure and exhaust gas temperature for the rated load point in both configurations are monitored in order to check that limits are not exceeded, especially regarding the limit on PCP which should not exceed 250 bar.

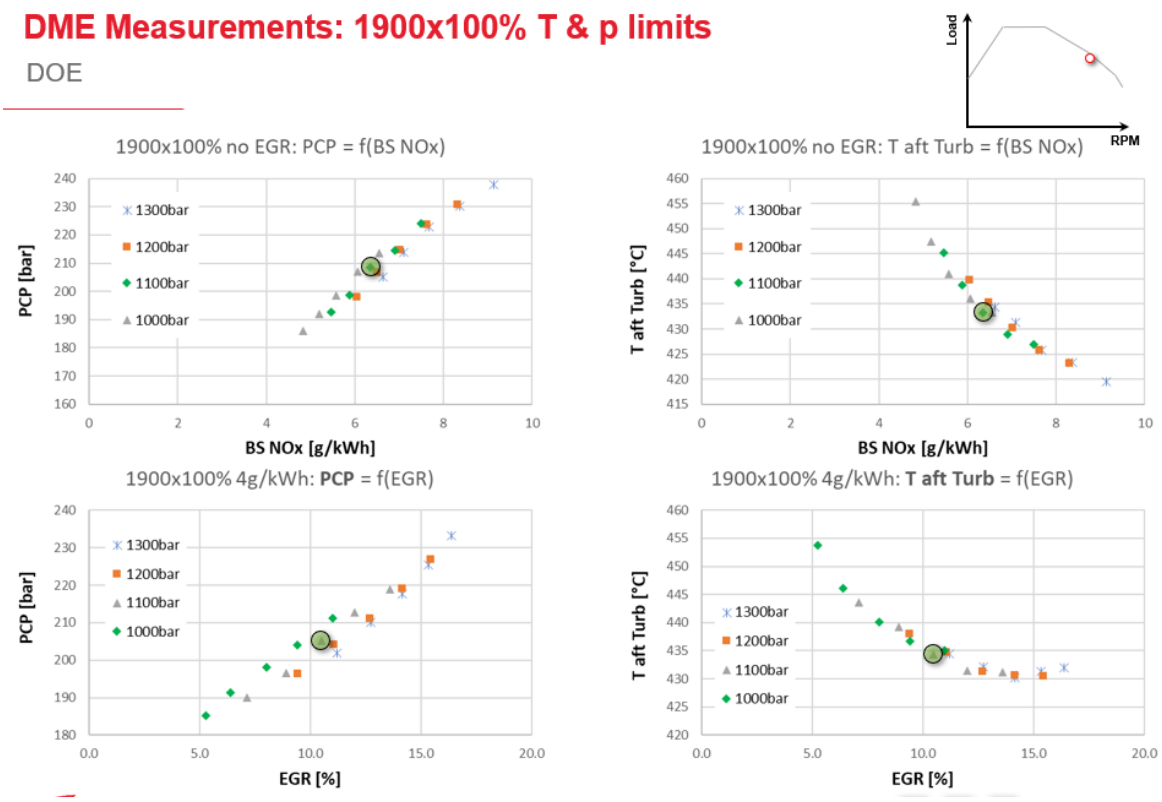



Figure 52: Peak Cylinder Pressure and Exhaust Gas Temperature resulting from the DoE results for the Cruise load points

## 4.8 Engine Calibration with no EGR at BS NOx = 8g/kWh

From the extensive carried out DoE, it was decided to calibrate the engine for a BS NOx = 8g/kWh. Using some special Matlab tools to create 3D surfaces and smooth them: Boost pressure, Rail pressure and start of injection in function of RPM and load (injection quantity) were defined as seen Figure 53.

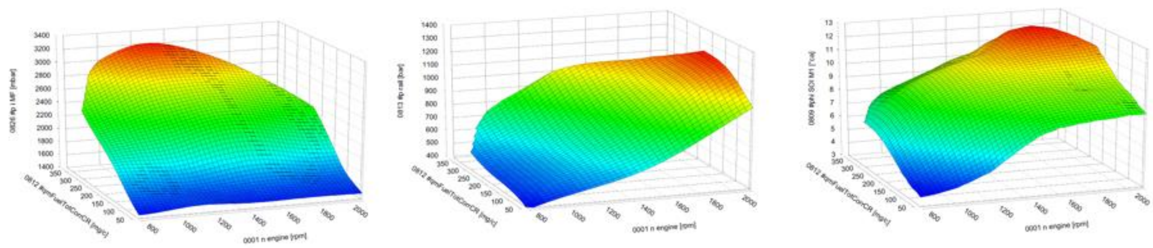


Figure 53: Calibrated Maps for Boost pressure, Rail Pressure and Start of Injection to reach a BS NOx = 8g/kWh without EGR.

Figure 54 is showing the Specific NOx in g/kWh for the whole engine map. In general, the BS NOx achieved is very close to the initial target of 8g/kWh above 30% load and between 900 rpm and 1500 rpm engine speed. At rated speed, BS NOx is lower at about 6.5 g/kWh.

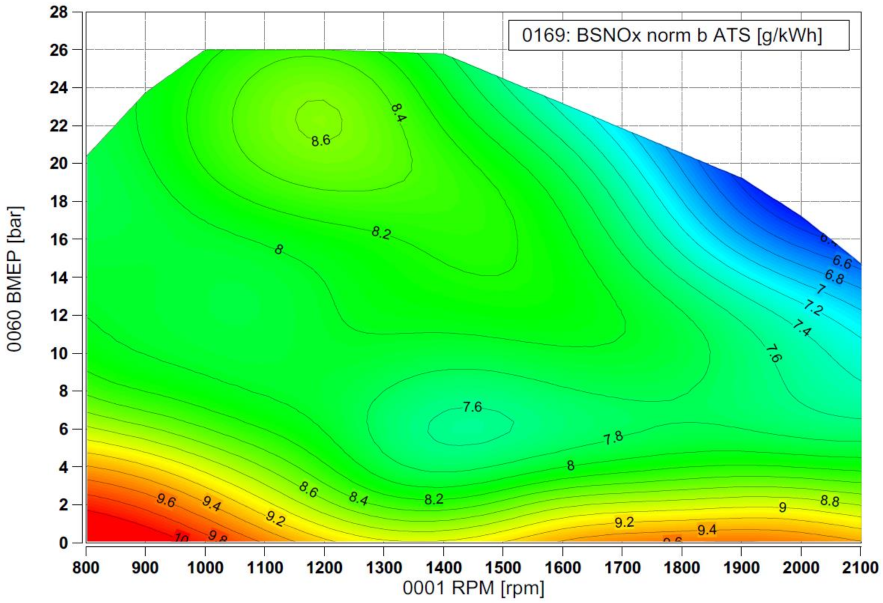



Figure 54: Specific NOx in the engine map in g/kWh

Brake Thermal Efficiency is seen Figure 55 where at least 43% is reached around the Cruise load point [1200 rpm x 9.8 bar]

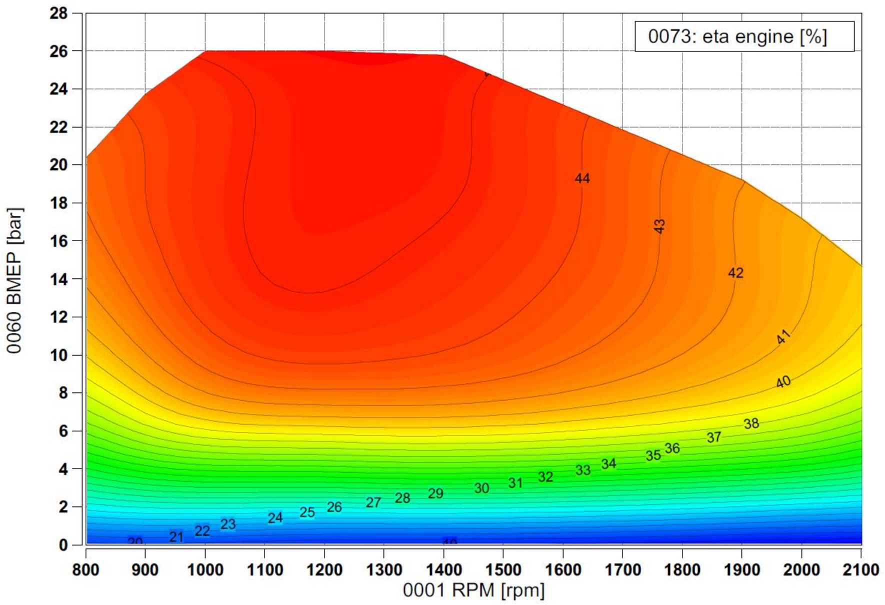



Figure 55: Brake Thermal Efficiency in engine map for no EGR and BS NOx = 8g/kWh

Exhaust gas temperature in the engine map is seen in figure 56. Above engine speed of 1500 rpm and load below 7 bar, temperatures are below 250°C and this could be critical for the ATS system however a heavy-duty truck would never spend much time in these areas of the engine map.

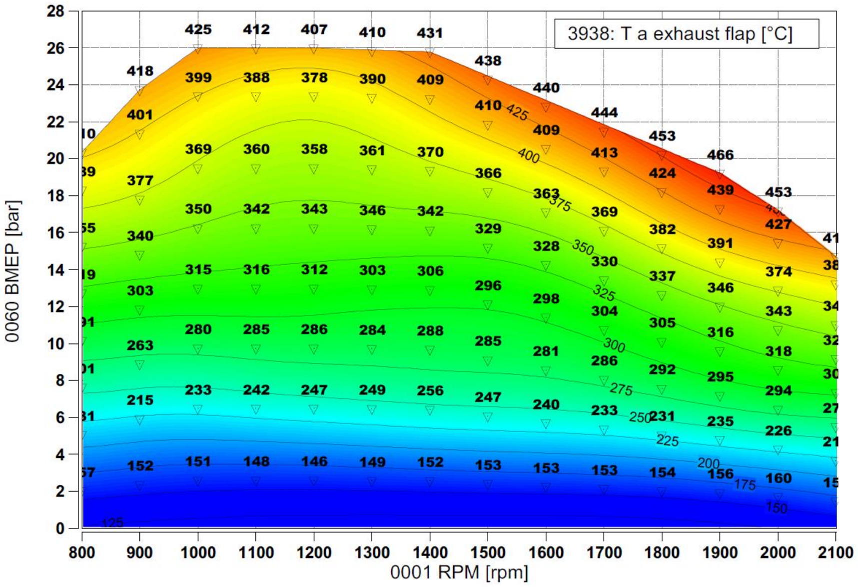



Figure 56: Exhaust gas temperature in Engine map for no EGR and BS NOx = 8g/kWh

Peak Cylinder Pressure are below the 250 bar which is the maximum design target pressure as seen in figure 57.

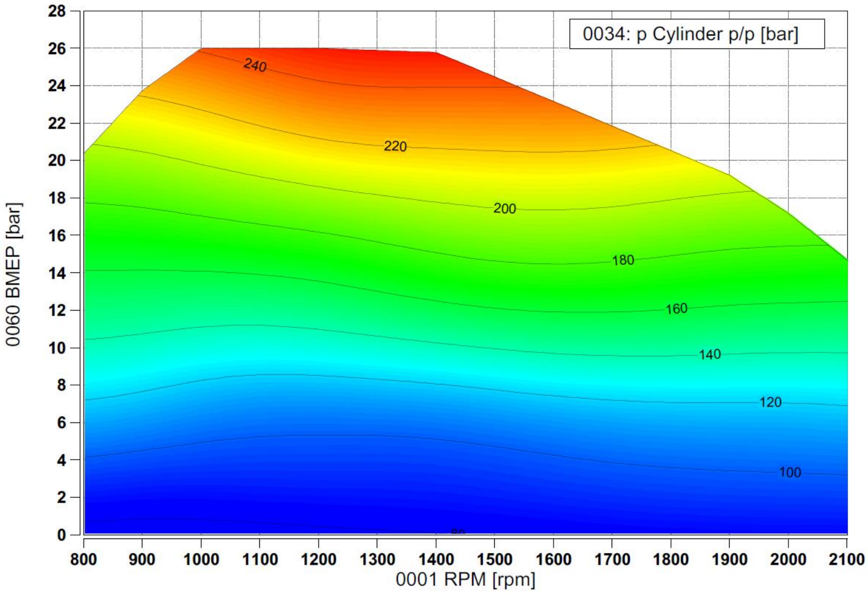



Figure 57: Peak Cylinder Pressure in Engine map for no EGR and BS NOx = 8g/kWh

Brake Specific $CO_2$ in g/kWh is shown in Figure 58. In general, $CO_2$ emissions are about 10% to 12% lower than an equivalent diesel engine.

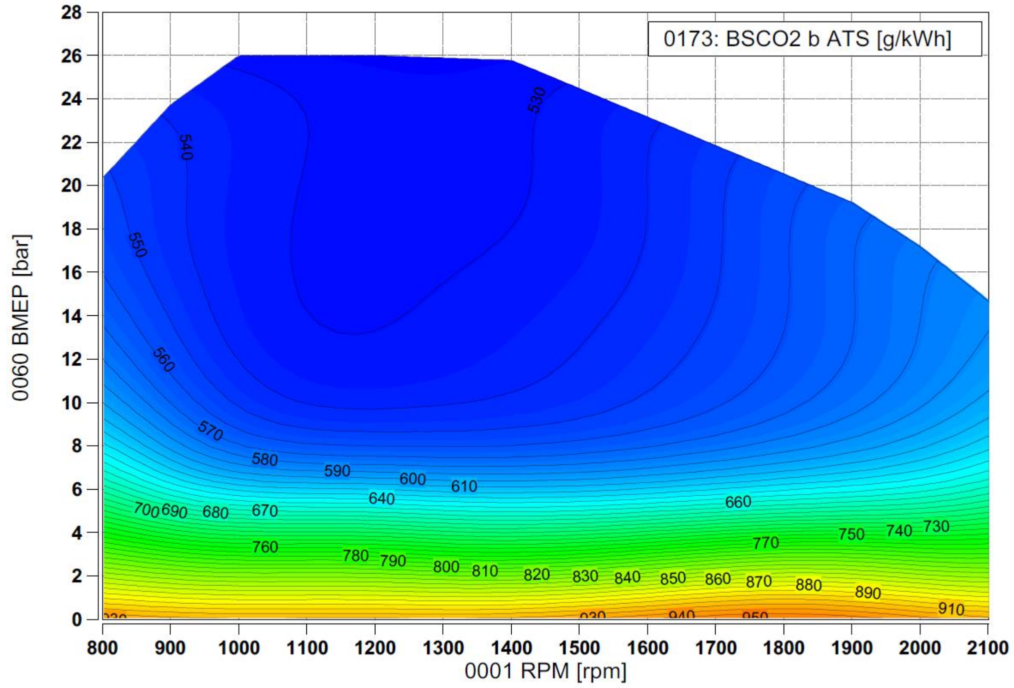



Figure 58: Brake Specific $CO_2$ in Engine map for no EGR and BS NOx = 8g/kWh

Figure 59 & 60 are showing the respective CO and HC emissions in the engine map. The values are very low confirming the good combustion set up even at low load.

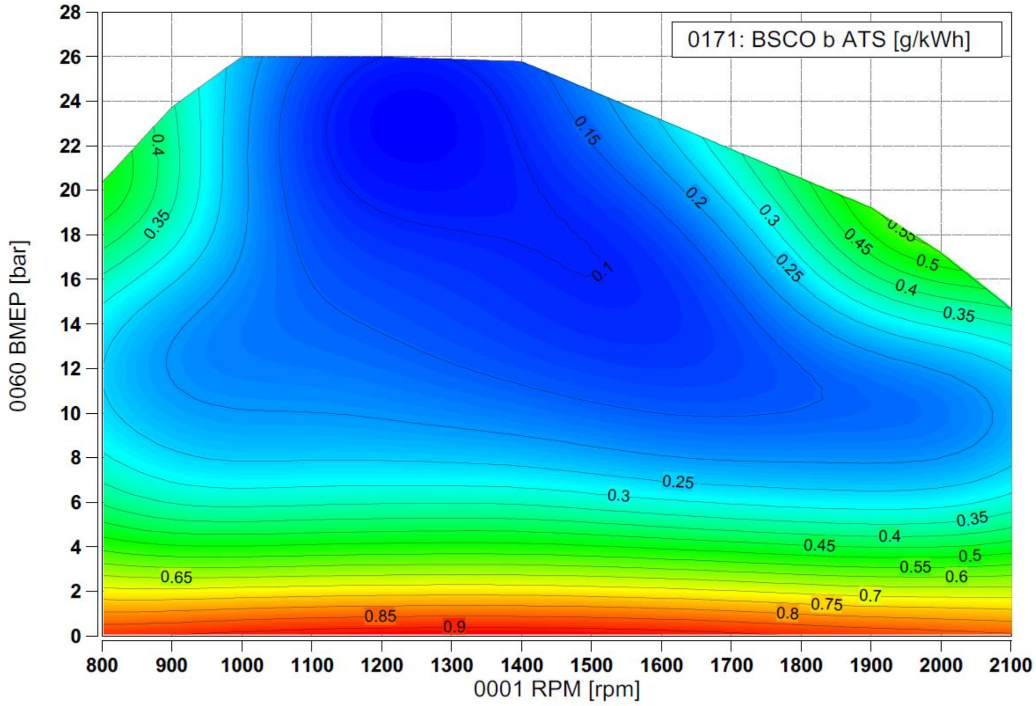



Figure 59: Brake Specific CO in Engine map for no EGR and BS NOx = 8g/kWh

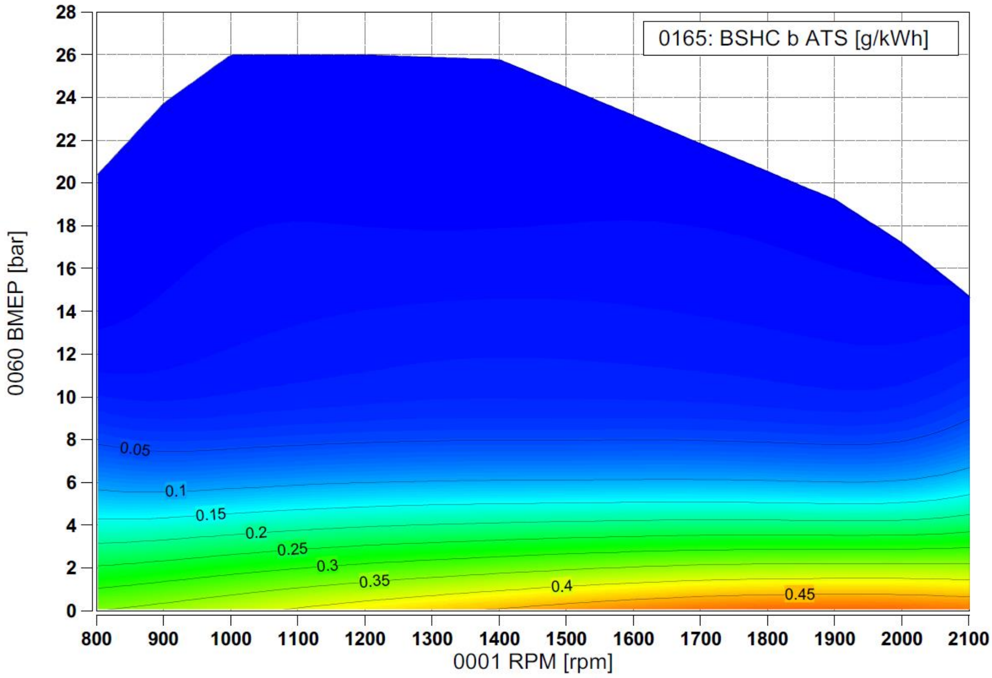



Figure 60: Brake Specific HC in Engine map for no EGR and BS NOx = 8g/kWh

## 4.9 WHTC

The WHTC test (Figure 61) is a transient engine dynamometer protocol representative of a world-wide pattern of heavy-duty commercial vehicle use. It consists in a transient test of 1800 s duration, with several motoring periods.

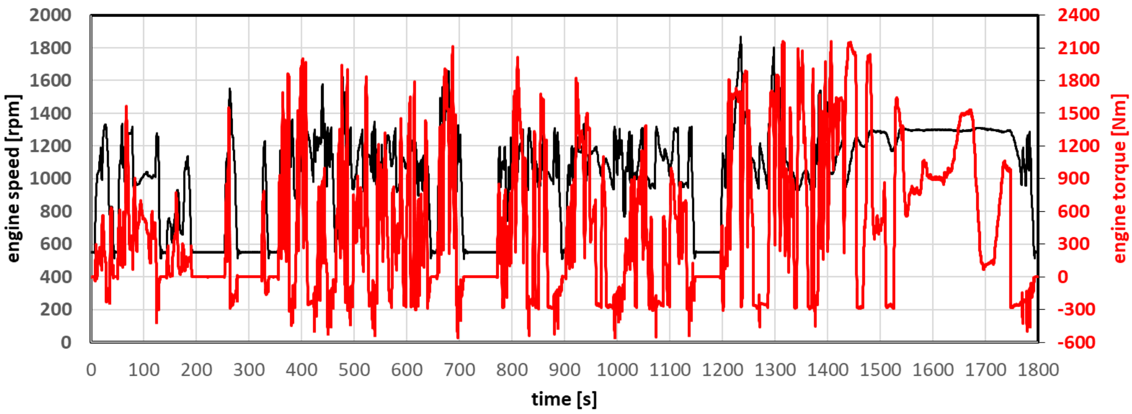



Figure 61: WHTC cycle pattern for engine speed and Torque

The WHTC was carried out in order to evaluate the engine out averaged emissions, the results can be seen in Table 5. Beside NOx, all emissions are already within the Euro VI tail pipe legislations. Tail pipe NOx emissions could be achieved with a 95% conversion rate, this will be investigated in the next paragraph related to ATS.

Compared with Tail pipe EUVI emissions limits, HC and CO emissions are almost one order of magnitude less whereas particle emissions are two orders of magnitude less.

| raw emissions (engine out)<br>fuel: DME | Specific<br>[g/kWh] | Diesel EUVI tailpipe limit (WHTC)<br>[g/kWh] |
|---|---|---|
| CO | 0.39 | 4 |
| CO2 | 589 | - |
| NOx | 7.8 | 0.46 |
| THC | 0.03 | 0.16 |
| PM (Micro Soot AVL) | 0.00014 | 0.01 |

Table 5: Averaged emission engine out for WHTC cycle

### 4.10 ATS Results

The ATS used with the DME engine on the testbed is of modular type which allows to reposition some components like the particle filter at the exit. All measurements are based on an engine calibration corresponding to a BS NOx engine out equal to 8g/kWh without EGR as shown in Figure 54 (page 46).

Figure 62 shows the individual components and their assembly with the heat insulation mattress on the testbed.


Figure 62: ATS Individual components

A schematic layout is shown in Figure 63 where the particle filter is located downstream the SCR catalysts.

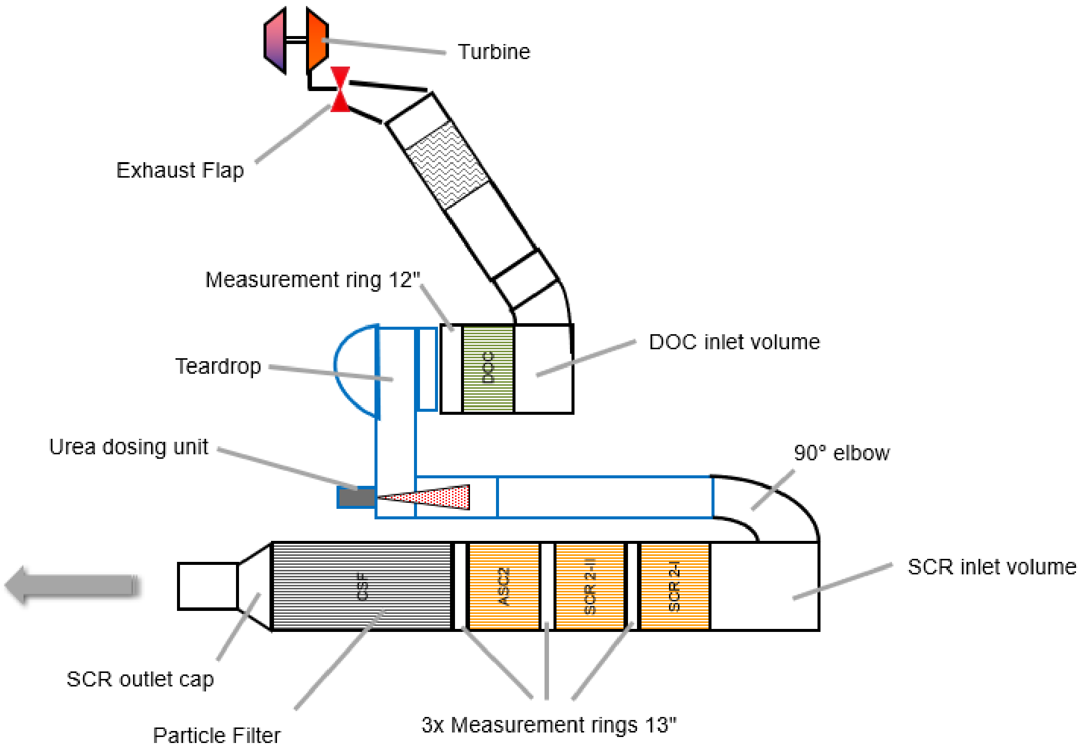



Figure 63: ATS Schematic Layout

The first set of measurements were realized at steady state for different load points using FTIR to identify emissions from individual species with and without ATS. Results can be seen Figure 64 were NOx emissions are dramatically reduced thanks to the SCR units whereas CO and $CH_2O$ (Formaldehyde) are close to zero as a result of the DOC oxidation process in excess of Oxygen.

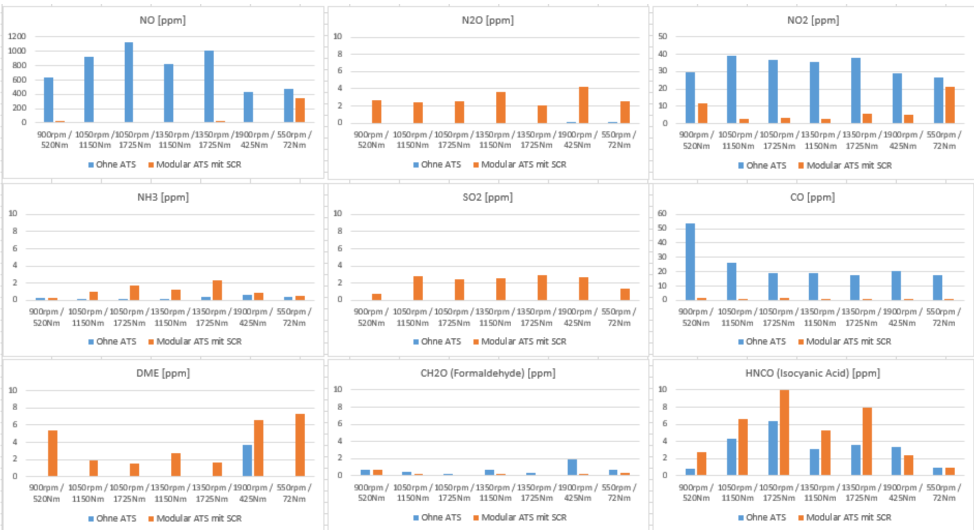



Figure 64: ATS emissions of characteristic species using FTIR at steady state

In Figure 65, the brake specific NOx at the tail pipe (after ATS) can be seen in the engine map when no thermal management is activated to increase exhaust temperature. Above the dosing temperature threshold corresponding to a load of 5-6 bars across the engine range, NOx emissions are well below EU6 target of 0.46g/kWh proving a very efficient conversion process of the ATS layout.

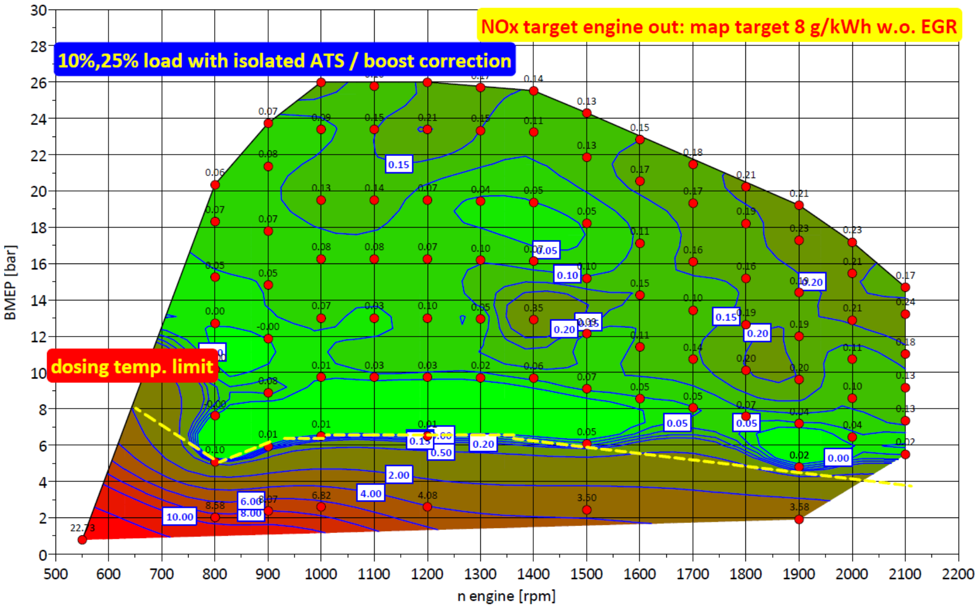



Figure 65: BS NOx emissions at tail pipe across the engine map

Regarding brake specific CO at the tail pipe, BS CO: very low levels have been achieved as seen Figure 66 across the engine map.

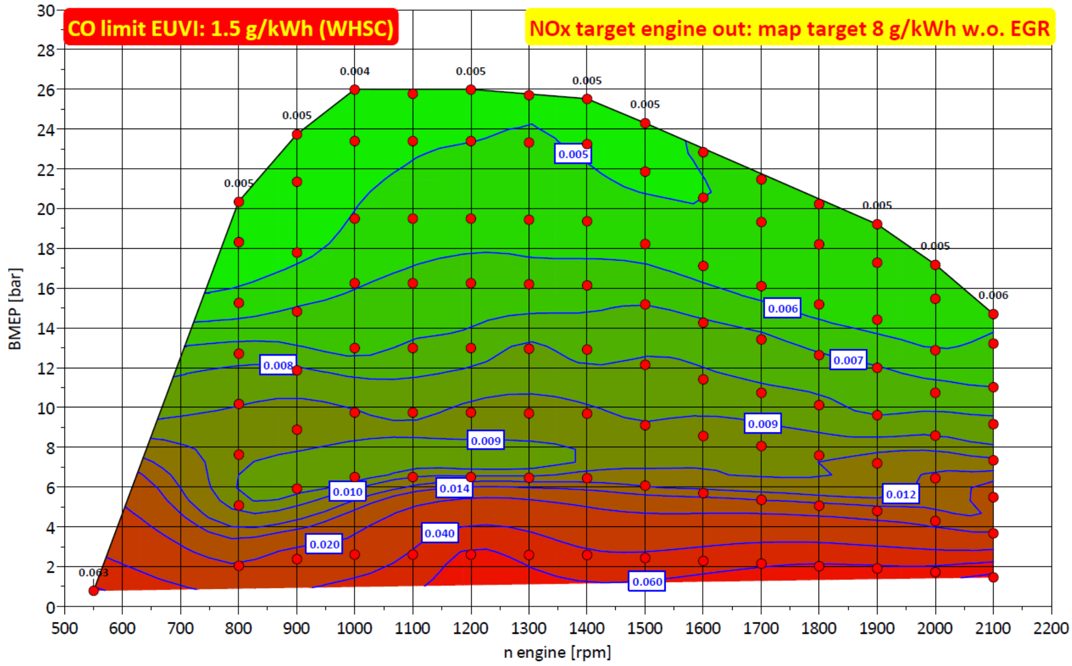



Figure 66: BS CO emissions at tail pipe across the engine map

Similar to the brake specific CO at the tail pipe, the THC emissions are very low as well: one order of magnitude less than the standard limit on HC as seen Figure 67 across the engine map.

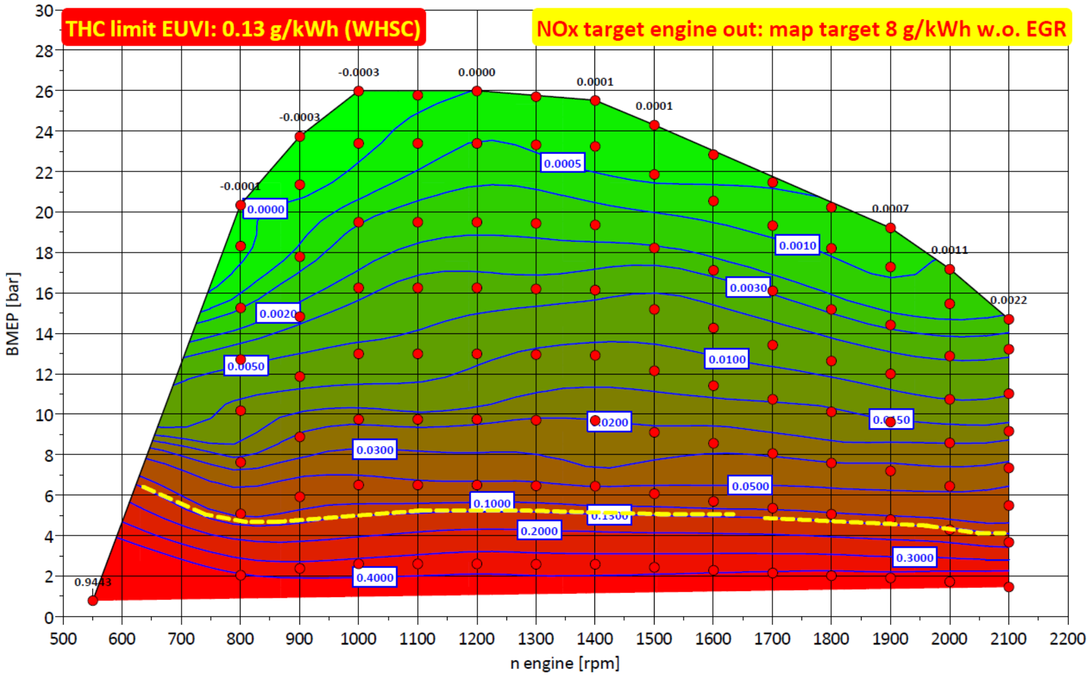



Figure 67: BS HC emissions at tail pipe across the engine map

Specific soot emissions measured with the AVL micro soot sensor shows extremely low level, close to zero on Figure 68.

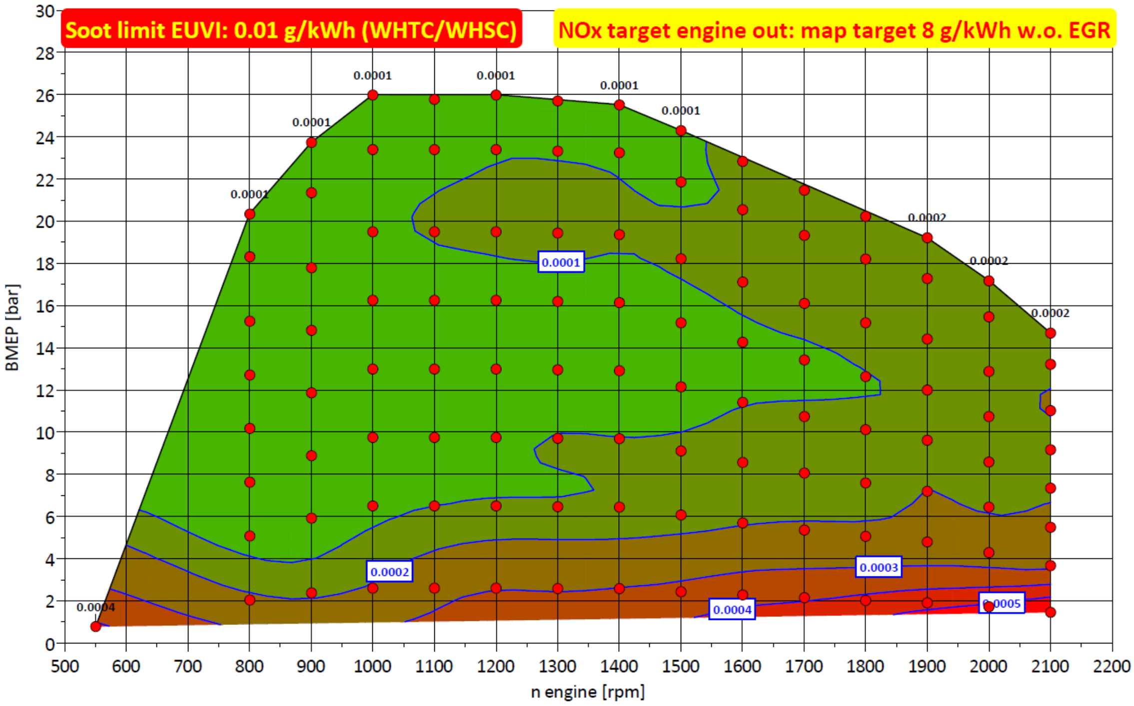



Figure 68: BS Soot emissions at tail pipe across the engine map

# 5 Conclusions

The current trend towards the future of mobility in Europe is Electrification and Hydrogen. These can cover a broad field of different applications where energy density (range, payload, continuous power) is not the most important criteria. However, it is becoming more clear that for many applications where the weight and the power demand of the operated machines (e.g. agriculture harvesting machines, trucks) is high, the ambient conditions challenging and the operating time long, only chemical energy carriers with higher energy densities than compressed H2 are viable solutions. Figure 69 is showing the suitable powertrain for a dedicated mission and the potential use of DME is shown within the dash line. From its thermophysical properties and molecular structure, DME is an ideal fuel for compression ignition engine, especially considering its' no-soot emission properties.

With the right combustion layout, this project could demonstrate that DME combustion, at very low NOx and HC emission level, is also very clean in terms of CO, THC, $N_2O$ and formaldehyde. Additionally, this project could show that an externally lubricated common-rail pump for DME is possible which renders the classical approach to add lubricity additive to DME unnecessary. This means that all in chapter 1.3 (Objectives, page 9) mentioned objectives could be achieved during this project execution.

DME is already produced in large quantities, mainly with methanol dehydration. The methanol-to-DME conversion process is practically loss-less [9] [10]. DME is currently used in industrial/pharmaceutical processes and as a non-toxic and ozone-layer friendly propellant in spray cans. Research and the DME industry is pushing heavily to establish production pathways for renewable rDME with waste products as input materials. Therefore, it seems to be possible to establish a "critical mass" in the industry and research community to push rDME as a promising solution for high power / long-distance applications.

DME is rather easy to handle as it can be kept in a liquid phase at a moderate pressure of 6 bars at 20°C, it is not toxic and with considerable TtW $CO_2$ reduction potential. Since DME has to be kept at moderate pressure, the fuelling process has to be performed with a tight system which has the advantage that the fuel handling process is free of spillage.
Low material compatibility, infrastructure spread and production capacities (within the EU) are the main hurdles for fast deployment. Current EU TtW $CO_2$ assessment will have to be changed in order to push bio-DME or e-DME fuels and make this solution attractive for the manufactures. However, Switzerland has the possibility to lead this way as the Swiss legislation provides the possibility to credit for the use of renewable fuels. And since renewable DME can be locally produced or physically imported, the proof of origin is much easier to achieve in contrast to feed-in of renewable gases or electricity abroad.
In order to come to a commercial product, Tier I OEM suppliers need to implement strategies in fuel system development for low viscosity and low boiling point fuels such as DME or Methanol in order to support the development of internal combustion engines with alternative fuels.
However, different stakeholders have different opinions on alternative fuels: the main challenge is to align OEMs, end customers, fuel companies, agencies and policy makers to enable application-specific promising solutions for maximum greenhouse gas reduction in a technology-open manner.
DME can be considered as such a promising solution for fleet operation (On/Off Road) with Bulk fuel delivery to operators.

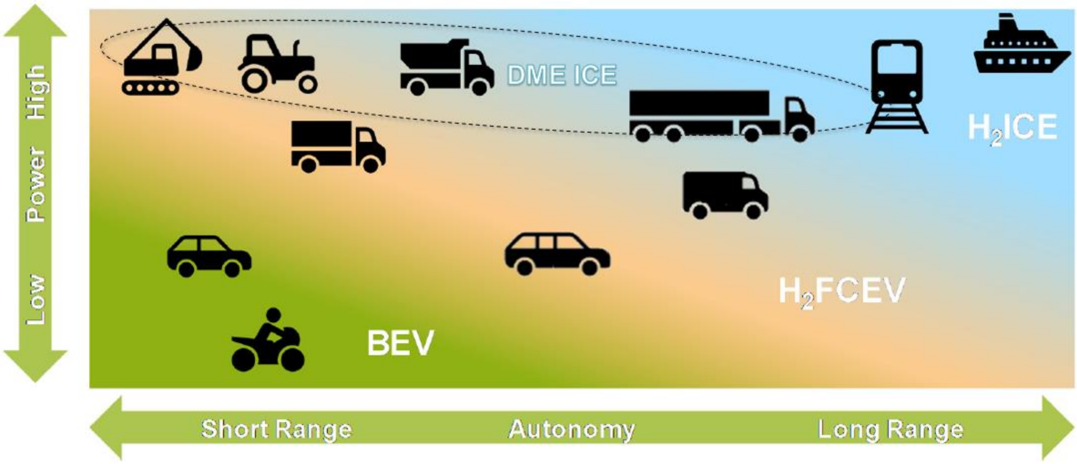



Figure 69: Suitable powertrain for dedicated mission vehicle
Source: BorgWarner's Injection System Solutions for Natural Gas and Hydrogen (30th Aachen Colloquium Sustainable Mobility 2021)

# 6 Outlook and next steps

- Proof of concept on a HD truck in Switzerland (Iveco Stralis from Motorex operating daily delivery service)

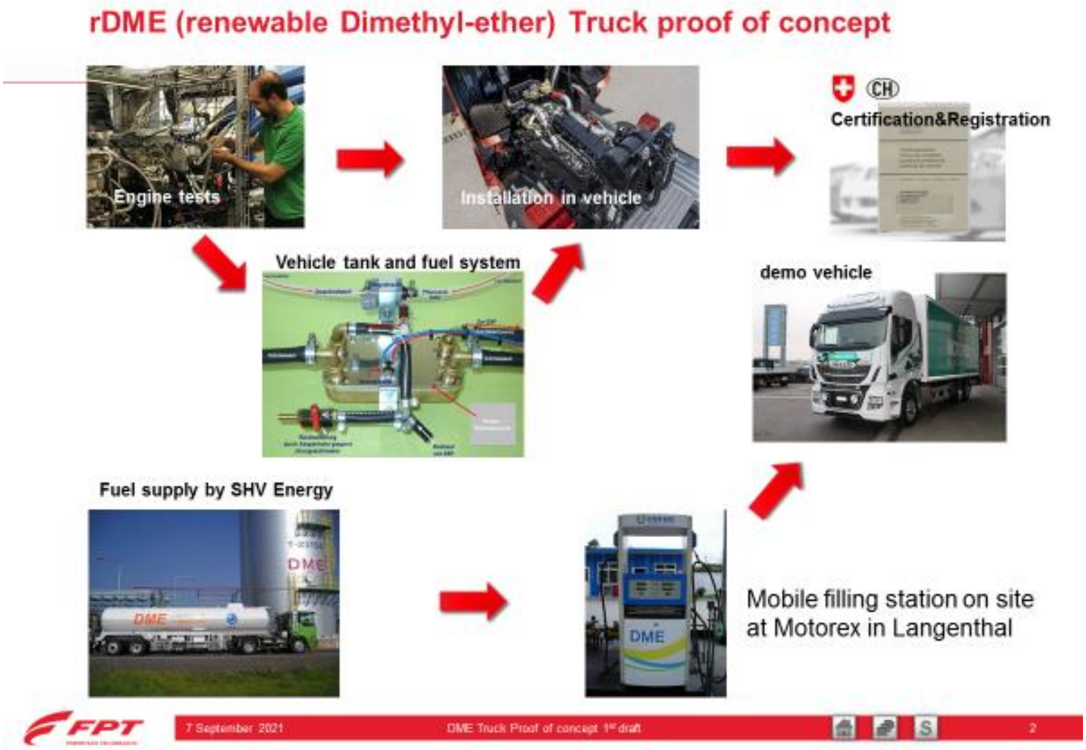



Figure 70: rDME proof of concept on a Motorex Stralis in daily delivery service

It is planned to put a vehicle into operation in the first half of 2022. One unexpected hurdle is the fuel import/taxation. Considering that the volumetric energy content of rDME is about half of that of Diesel, the taxation is about doubled (Table 5 on the next page). This is boosting the cost unnecessarily and does not makes sense for a fuel with lower $CO_2$ emissions

It is intended to use rDME but this does not really help as to profit from zero taxation, a verification that this rDME has never been in contact with any fossil DME in the whole supply chain is a very long, elaborate and thus expensive process. The rather small amount of fuel estimated to be around 40’000 litres/year for this project, does not justify starting such a costly process.

The main purpose of this project is to gain experience in terms of DME fuel system installation in the vehicle. To keep DME fluid in the low-pressure fuel system is more challenging than in the test cell as there is no water @ 8-10°C available for the fuel coolers. A suitable solution must be found to keep the fuel fluid under all conditions. Based on this experience we can transfer knowledge to the below mentioned Off-Highway projects.

| | Diesel | Propan | DME gem. Minst.gesetz | Bio-DME | CNG (Normal-steuersatz) | CNG (red. Steuersatz) | | |
|---|---|---|---|---|---|---|---|---|
| MinÖst | 0.4587 CHF/l (1) | 0.0830 CHF/l (1) | 0.4260 CHF/l (1) | 0.0000 CHF/l (2) | 0.4099 CHF/kg (1) | 0.1125 CHF/kg (1) | Steuersätze pro Masse | |
| MinÖst-Zuschlag | 0.3000 CHF/l (1) | 0.1260 CHF/l (1) | 0.3000 CHF/l (1) | 0.0000 CHF/l (2) | 0.3990 CHF/kg (2) | 0.1097 CHF/kg (1) | Steuersätze pro Volumen | |
| **Minöst-Total** | **0.7587 CHF/l** | **0.2090 CHF/l** | **0.7260 CHF/l** | **0.0000 CHF/l** | **0.8089 CHF/kg** | **0.2222 CHF/kg** | | |
| Dichte (@15°C) | - - - | | - - - | - - - | 0.75 | 0.75 | CNG: | http://www.google.c |
| [kg/l] (@15°C) | 0.835 | 0.506 | 0.677 | 0.677 | - - - | - - - | Be/Di: | Gemäss Energieetike |
| | | | | | | | Propan: | https://www.propan. |
| Heizwert | - - - | | - - - | - - - | 10.23 kWh/m3 | 10.23 kWh/m3 | CNG: | gemäss Swissgas 201 |
| (Vol. @15°C) | 11.65 kWh/kg | 12.87 kWh/kg | 7.89 kWh/kg | 7.89 kWh/kg | - - - | - - - | Be/Di: | Gemäss Energieetike |
| | 9.730 | 6.512 | 5.343 | 5.343 | 13.615 kWh/kg | 13.615 kWh/kg | Propan: | https://www.propan. |
| **Spez. Steuer CHF/kWh** | **0.0780** | **0.0321** | **0.1359** | **0.0000** | **0.0594** | **0.0163** | | |

(1): Gemäss Mineralölsteuergesetzt vom 21. Juni 1996 (Stand 1. juli 2020)
(2): Gemäss Mineralölsteuerverordnung vom 20. November 1996 (Stand 1. Januar 2021)

Table 6: Comparison of fuel taxation in Switzerland

- Project idea for Off-Highway applications (Sugar Cane Harvester and Farm truck in Brazil) for funding submission to demonstrate circular economy

- **Product:** DME Sugar Cane Harvester and heavy farm truck
- **Project Content:**
  - Adapt current C11 used into Sugar Cane Harvester machine to DME fuel without ATS
  - Vehicle fuel system adaptation to DME specific requirements (tank and low pressure fuel system)
  - Development of C13 DME at Empa for HD truck
  - Adaptation of heavy farm truck to DME (fuel tanks)
  - Installation of C13 DME in a farm truck operating at 150T GVW
  - Field test with both machines to demonstrate business case
- **Expected Benefits:**
  - Use crop agriculture residuals for fuel production →100% Renewable fuel produced directly on site or close to
  - Demonstrate interesting business case for circular economy


Figure 71: DME in an Ethanol plant from Brazil

# 7 National and international cooperation

National cooperation with

**Empa**, Swiss Federal Laboratories for Materials Testing. Empa was doing the major part of WP1 regarding infrastructure and test cell installation. All engine experiments were performed at Empa.

**Bucher AG (Motorex)**, Langenthal with Robert Lea, Dr. Markus Kurzwart and Markus Staubli to support regarding Lubrication in general and engine oil and additive composition to meet the requirements related to this alternative fuel type.

International cooperation with

**Nouryon** (former AkzoNobel Industrial Chemicals B.V.), Amsterdam, The Netherlands. Nouryon is Europe's largest producer of DME with production of 55'000 tons per year in their DME plant in Rotterdam. Basically, DME is produced from methanol, which is produced from fossil natural gas or biogas. However, alternative and renewable paths to produce DME are a strategic goal of Nouryon and they are in the pilot phase, together with partners, to establish a "Waste-to-DME" production in the Port of Rotterdam. Nouryon expressed its interest to be closely integrated in this project. FPT and Empa agreed that Nouryon will supply DME fuel for this project via their closest distributor Settalagas (Milano, Italy).
**PoliMi**: The Internal Combustion Engine Group led by Prof. Onorati was responsible for the integration of DME's reaction kinetic mechanisms into libICE which is a set of dedicated libraries to run CFD combustion simulation within OpenFOAM. PoliMI was supporting the optimisation of the DME's combustion chamber with dedicated methodologies.
**Bosch:** Bosch Stuttgart (D) for Bosch internal coordination to support this project, Bosch Steyr (A) as the technical experts center for Injectors and Bosch Bari (I) as the technical experts center for the high pressure eSV pump

# 8 Publications / Conferences

- Gilles Hardy, Daniel Klein, Patrik Soltic, Thomas Hilfiker, Tommaso Lucchini, Andrea Schirru, DME as an Alternative Fuel for Compression Ignition Engines in Long-Haul Heavy-Duty Transport, SAE Paper 2021-24-0065 (to be resubmitted)
- Gilles Hardy, Investigation of the suitability of DME as an alternative fuel in heavy-duty vehicles, Conference on Combustion Research in Switzerland 2021, September 17th, 2021, Zürich
- Gilles Hardy, use of e-fuels: ICE potential for Heavy-duty applications, e-fuels Prospects in production and use, Politecnico of Milano, October 5th, 2021, Milan
- Gilles Hardy, DME: an alternative fuel suitable for heavy-duty machinery, Green Non-Road Mobile Machinery Forum 2021, October 7th, 2021, Webinar
- Andrea Schirru, Tommaso Lucchini, Gianluca D'Errico, Marco Mehl, Gilles Hardy, Patrik Soltic, Combustion Modeling in a Heavy-Duty Engine operating with DME using detailed kinetics and turbulence chemistry interaction, submitted to SAE WCX 2022

**The authors are aware of the following media reports about this project:**

**Print / German**

| | |
|---|---|
| Die Baustellen 22.12.20 | Flüchtiges für Trucks |
| Neue Zürcher Zeitung 05.12.20 | Sauberer Treibstoff geht ins Geld |
| Strasse und Verkeh21.12.20 | Flüchtiges für schwere Lastwagen |
| Umwelttechnik Schweiz 31.12.20 | Flüchtiges für schwere Lastwagen |
| ChemieXtra 19.04.21 | Treibstoff für Lastwagen: Dimethylether |
| Aktuelle Technik 12.04.21 | Grüne Treibstoffe aus erneuerbaren Ressourcen |
| Umwelt Perspektiven 09.03.21 | Flüchtiges für schwere Lastwagen |
| Swiss Engineering STZ 04.02.21 | Antriebstechnik: Flüchtiges für schwere Lastwagen |
| TIR transNews 21.01.21 | Flüchtiges für schwere Lastwagen |
| TIR transNews 21.01.21 | Diese Menschen bewegen unsere Transportbranche |
| news-research.net 22.01.21 | FPT Industrial leitet ein von der Schweiz finanziertes Projekt für alternative Kraftstoffe in Hochleistungsmotoren |
| presse-blog.com 21.01.21 | FPT Industrial leitet ein von der Schweiz finanziertes Projekt für alternative Kraftstoffe in Hochleistungsmotoren |

**Print / French**

| | |
|---|---|
| Swiss Engineering RTS 06.08.20 | Comment améliorer le rendement des moteurs Diesel et les rendre plus propres |
| Int. Transport Journal 15.01.21 | Du volatil pour du lourd |

**Print / English**

| | |
|---|---|
| Int. Transport Journal 15.01.21 | Volatitlity for the heavies |

**Internet / German**

| | |
|---|---|
| immittelstand.de 24.11.20 | Flüchtiges für schwere Lastwagen |
| mynewschannel.net 24.11.20 | Flüchtiges für schwere Lastwagen |
| news-blast.com 24.11.20 | Flüchtiges für schwere Lastwagen |
| newsonline24.net 24.11.20 | Flüchtiges für schwere Lastwagen |
| news-research.net 24.11.20 | Flüchtiges für schwere Lastwagen |
| presse-blog.com 24.11.20 | Flüchtiges für schwere Lastwagen |
| Springer 02.12.20 | Empa testet Dimethylether als alternativen Treibstoff für Lkw |
| laborpraxis.vogel.de 01.12.20 | Werden Lastwagen bald ein Vorbild im Klimaschutz? |
| mm-logistik.vogel.de 01.12.20 | Werden Lastwagen bald ein Vorbild im Klimaschutz? |

| | |
|---|---|
| energie-cluster.ch 27.11.20 | Diesel-Alternative |
| str-online.ch 27.11.20 | Flüchtiges für schwere Lastwagen |
| tir-transnews.ch 26.11.20 | Treibstoff aus erneuerbarer Energie für Dieselmotor |
| agrartechnik.ch 25.11.20 | Empa testet Dimethylether für Lkw-Einsatz |
| focus.de 25.11.20 | Könnte Dimethylether zukünftig Lastwagen antreiben? |
| Ingenieur Karriere 25.11.20 | Die Lösung für den Güterverkehr: chemischer Treibstoff für Lkw |
| Innovation Origins 25.11.20 | Dimethylether anstatt Diesel – so werden LKWs sauber |
| Intern. Verkehrswesen 25.11.20 | DME als Alternativtreibstoff: Flüchtiges für schwere Lasten |
| moneycab.com 25.11.20 | Flüchtiges für schwere Lastwagen |
| Natur.de 25.11.20 | Könnte Dimethylether zukünftig Lastwagen antreiben? |
| Top Agrar Online 25.11.20 | Dimethylether als neuer Lkw-Treibstoff |
| wirtschaftsraum-zuerich.ch 25.11.20 | Empa forscht an Alternative zu Diesel |
| wissenschaft.de 25.11.20 | Könnte Dimethylether zukünftig Lastwagen antreiben? |
| baublatt.ch 24.11.20 | Nutzfahrzeuge: Ökologischer Fahren mit Dimethylether |
| circular-technology.com 24.11.20 | Dimethylether – eine nachhaltige Alternative zu Diesel? |
| energate-messenger.ch 24.11.20 | Empa testet Chemikalie als Dieselersatz |
| industriebox.de 24.11.20 | Flüchtiges für schwere Lastwagen |
| Innovations-Report.de 24.11.20 | Flüchtiges für schwere Lastwagen |
| juraforum.de 24.11.20 | Flüchtiges für schwere Lastwagen |
| Pressebox 24.11.20 | Flüchtiges für schwere Lastwagen |
| punkt4.info 24.11.20 | Empa forscht an Alternative zu Diesel |
| technologiebox.de 24.11.20 | Flüchtiges für schwere Lastwagen |
| industriebox.de 21.02.21 | FPT Industrial leitet ein von der Schweiz finanziertes Projekt für alternative Kraftstoffe in Hochleistungsmotoren |
| press.lectura.de 22.02.21 | FPT Industrial leitet ein von der Schweiz finanziertes Projekt für alternative Kraftstoffe in Hochleistungsmotoren |
| presseradar.de 22.02.21 | FPT Industrial leitet ein von der Schweiz finanziertes Projekt für alternative Kraftstoffe in Hochleistungsmotoren |
| konstruktion-industrie.com 21.02.21 | FPT Industrial leitet ein von der Schweiz finanziertes Projekt für alternative Kraftstoffe in Hochleistungsmotoren |

**Internet / French**

| | |
|---|---|
| str-online.ch/fr/ 27.11.20 | Dimethylether – le prochain éco-carburant pour les camions? |
| industrie-afrique-du-nord.com 21.02.21 | Projet sur les carburants alternatifs pour les poids lourds |
| ChantiersdeFrance.fr 01.02.21 | Motorisation – FPT s’intéresse aux carburants alternatifs |

**Internet / Italian**

| | |
|---|---|
| DieselWeb.eu 31.01.21 | FPT e il DME: Il carburante alternativo |
| BY Innovation 28.01.21 | DME carburanti alternativi |
| Automazione Plus 26.01.21 | Un progetto per il carburante alternativo su motori per veicoli pesanti |
| Lulop.com 21.01.21 | FPT industrial a capo di un progetto finanziato da fondi svizzeri per il carburante alternativo su motori per veicol ... |
| tuttosprint.ch 21.01.21 | FPT Motorenforschung di Arbon e la grande sfida |

**Internet / Portuguese**

| | |
|---|---|
| engenharia-brasil.com 21.02.21 | Combustiveis alternativos em motores de veiculos pesados |
| Brasil do Trecho 25.01.21 | Iveco vem trabalhando para motorização alternativo |
| CIMM 22.01.21 | FPT Industrial lidera projeto financiado na Suíça para combustíveis alternativos e motores de veículos pesados |
| Diário do Transporte 22.01.21 | FPT Industrial lidera projeto na Suíça para o uso do DME, combustível alternativo limpo para motores de veículos pesados |

**Internet / Spanish**

| | |
|---|---|
| interempresas.net 21.04.21 | FPT Industrial prueba un combustible alternativo en un motor |
| soloindustria.com 28.01.21 | FPT Industrial dirige un proyecto de combustible alternativo |
| Economia de Hoy.es 22.01.21 | FPT Industrial dirige un proyecto de combustible alternativo para motores de gran potencia con financiación suiza |
| revista-fabricacion.com 21.01.21 | FPT Industrial dirige un peoyecto de combustible… |

**Internet / English**

| | |
|---|---|
| Green Car Congress 30.11.20 | Empa and partners exploring DME as fuel with new heavy-duty test engine |
| Innovation Origins 25.11.20 | Dimethyl-Ether instead of diesel – how trucks can become cleaner |
| textile-future.com 25.11.20 | Sustainable fuels – Volatile stuff for heavy trucks |
| Innovations Report 24.11.20 | Volatile stuff for heavy trucks |
| worldindustrialreporter.com 19.11.20 | Dimethyl-Ether: A Cleaner Fuel Alternative for Commercial Fleets |
| mynewschannel.net 30.01.21 | FPT Industrial leads a swiss funded project for alternative fuel in heavy-duty engines |
| news-research.net 25.01.21 | FPT Industrial leads a swiss funded project for alternative fuel in heavy-duty engines |

| | |
|---|---|
| newsonline24.net 21.01.21 in | FPT Industrial leads a swiss funded project for alternative fuel heavy-duty engines |
| presse-blog.com 21.01.21 | FPT Industrial leads a swiss funded project for alternative fuel in heavy-duty engines |

**Internet / Dutch**

| | |
|---|---|
| Innovation Origins 25.11.20 | Dimethylether in plaats van diesel maakt vrachtauto schoner |

**Internet / Czech**

| | |
|---|---|
| Technicky Tydenik 02.02.21 | [FPT entwickelt Biokraftstoff für Dieselmotoren] |

**Internet / Hungarian**

| | |
|---|---|
| agroinform.hu 16.02.21 | [Die Zukunft der Kraftstoffe] |

**Internet / Chinese**

| | |
|---|---|
| industrysourcing.cn 22.02.21 | [Fiat Power Technology leitet ein von der Schweiz finanziertes Projekt für Hochleistungsmotoren mit alternativen Kra ... |
| auto.scol.com.cn 21.02.21 | [Fiat Power Technology leitet ein von der Schweiz finanziertes Projekt für Hochleistungsmotoren mit alternativen Kra ... |
| LMJX.net 19.02.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |
| Auto.ogel.com.cn 27.01.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |
| 21dianyuan.com 25.01.21 | [Fiat Power Technology leitet ein von der Schweiz finanziertes Projekt für Hochleistungsmotoren mit alternativen Kra ... |
| Chexun.com 21.01.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |
| Cn.China.cn 21.01.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |
| East Money 21.01.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |
| kuaibao.qq.com 21.01.21 | [Fiat Power Technology leitet ein von der Schweiz finanziertes Projekt für Hochleistungsmotoren mit alternativen Kra ... |
| Money Compass 21.01.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |

| | |
|---|---|
| SCI99.com 21.01.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |
| chinacar.com.cn 20.01.21 | [Fiat Power Technology leitet ein von der Schweiz finanziertes Projekt für Hochleistungsmotoren mit alternativen Kra ... |
| ECV360.com 19.01.21 | [Fiat Power Technologies leitet ein von der Schweiz finanziertes Schwerlast-Motorenprojekt für alternative Kraftstoffe] |

# 9 References


[1] Semelsberger TA, Borup RL, Greene HL. Dimethyl-Ether (DME) as an alternative fuel. J Power Sources 2006;156:497–511. https://doi.org/10.1016/j.jpowsour.2005.05.082.

[2] Erdener H, Arinan A, Orman S. Future fossil fuel alternative; Di-methyle ether (DME) A review. Int J Renew Energy Res 2011;1:252–8. https://doi.org/10.20508/ijrer.95502.

[3] Styring P, Dowson GRM, Tozer IO. Synthetic Fuels Based on Dimethyl-Ether as a Future Non-Fossil Fuel for Road Transport From Sustainable Feedstocks. Front Energy Res 2021;9:1–22. https://doi.org/10.3389/fenrg.2021.663331.

[4] Chapman EM, Boehman A, Wain K, Lloyd W, Perez JM, Stiver D, et al. Impact of DME-Diesel Fuel Blend Properties on Diesel Fuel Injection Systems. 2003.

[5] Rüdisüli M, Teske SL, Elber U. Impacts of an increased substitution of fossil energy carriers with electricity-based technologies on the Swiss electricity system. Energies 2019;12. https://doi.org/10.3390/en12122399.

[6] Brandes J, Haun M, Senkpiel C, Kost C, Bett A, Henning H-M. Wege zu einem klimaneutralen Energiesystem 2050 - Update unter einer Zielvorgabe von 65% $CO_2$-Reduktion in 2030 und 100% in 2050. 2020.

[7] Iannuzzi SE, Barro C, Boulouchos K, Burger J. Combustion behavior and soot formation/oxidation of oxygenated fuels in a cylindrical constant volume chamber. Fuel 2016;167:49–59. https://doi.org/10.1016/j.fuel.2015.11.060.

[8] Park SH, Lee CS. Combustion performance and emission reduction characteristics of automotive DME engine system. Prog Energy Combust Sci 2013;39:147–68. https://doi.org/10.1016/j.pecs.2012.10.002.

[9] Patten J, McWha T. Dimethyl-Ether fuel literature review. 2015. https://doi.org/10.4224/23000192.

[10] Pontzen F, Liebner W, Gronemann V, Rothaemel M, Ahlers B. $CO_2$-based methanol and DME - Efficient technologies for industrial scale production. Catal Today 2011;171:242–50. https://doi.org/10.1016/j.cattod.2011.04.049.