Hydrogen combustion engine – A suitable concept for Decarbonisation in Offroad sector

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Abstract
The global target of Greenhouse gases (GHG) reduction for 2050 is one of the focus on selection and definition of the future power train in several business sectors. The EU has agreed on new regulations to limit the CO2 emissions of new heavy-duty vehicles by 15% from 2025 and by 30% (or higher) from 2030 considering 2020 as reference. The off-road sector expects similar emission reduction targets.

Hydrogen, as a combustion fuel, represents an alternative and efficient solution for decarbonisation of future powertrains in the Off-road sector. The combustion of hydrogen is possible thanks to new system configurations. Injection technology, air path configuration and ignition technology are among the most notable system characteristics.

This new solution shall be convenient to operate in harsh environments and offer a lower product cost compared to other zero emission technologies. Furthermore, the new engine architecture shall ensure easier engine integration, higher power density, better system efficiency and higher lifetime. The dual fuel (DF) and direct injection (DI) technologies stand among the possible solutions to a relevant hydrogen powertrain. Their distinctive configurations regarding the above-mentioned system characteristics enables the assessment of each characteristic and that of their combination. The air path plays an important role in engine performance, dynamic behavior and emission compliance. Two-stage charging system and single stage with EGR are two possible air path configurations capable to ensure ultra-lean combustion. The later aims are to lower NOx emissions and increase power density.

The technology is robust and ensures a quick time to market thanks to unchanged vehicle interfaces. Besides the advantages of this hydrogen technology, there are some challenges that this technology has to face. The main challenge is to reach an acceptable hydrogen storage volume able to guarantee the typical working time of an off-road machine.

Key words

ICE : Internal combustion engine
DI : Direct injection
PFI : Port fuel injection
DF : Dual fuel
ZE : Zero-emission
ZEP : Zero-emission powertrain
EGR : Exhaust gas recirculation

1 Introduction

Diesel combustion engines have been for many years the reference solution for heavy-duty and off-road applications. Its strong presence in both sectors mainly results from its robustness, its high transient performance and its high efficiency.

As energy shortage threatens and strict emission regulations become effective, the development of alternative powertrains based on cleaner and renewable energy becomes essential. Zero-emission and low-emission technologies are among the main vectors to ensure the meeting of the CO2 emission reduction targets. Several milestones, defined by EU-Regulations for the On-Road heavy-duty sector, target a 15% reduction by 2025 and a 30% reduction by 2030. The set targets use 2020 CO2 emission values as reference.

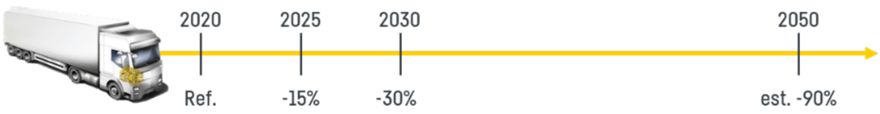

Figure 1 : EU CO2 emissions target for heavy duty vehciles

In order to satisfy the current regulation, three main zero emission (ZE) technologies prevail:

- **BEV** : Battery Electric Vehicle
- **FC** : Fuel Cell
- **ICE** : Internal Combustion Engine (with hydrogen or other decarbonized fuels)

These technologies fall in the category of Zero Emission Powertrains (ZEP) that require emissions of less than 1gCO2/kWh. This stringent tolerance still allows some residuals such as emissions due to the burning of engine oil in the combustion chamber. It is very important to keep in mind also that emission regulations are expected to change towards a Well-to-Wheel approach in the near future. Emissions will therefore consider all steps of the fuel production, transport and consumption.

The hydrogen ICE stands as a strong contestant in the ZEP landscape. As long as the technology can carry the strengths of the diesel combustion engine, it can become the go-to solution for the heavy-duty sector. To do so, it has to match the peak load performance, the transient behavior and the robustness of its diesel equivalent. This will not come easy considering hydrogen is a very different fuel compared to todays carbonated fuels. Following table gathers some of the properties of hydrogen compared to diesel and methane:

	Unit	Diesel	Methane	Hydrogen
Lower heating value	MJ/kg	42.8	50	120
Density @ 15°C	kg/m3	840	0.7 (gas)	0.09 (gas)
Stochiometric air requirement	[-]	0.5 - 2.0	0.6 - 2.0	0.13 - 10
Minimum ignition energy at Lambda = 1	mJ	0.24	0.29	0.02
auto Ignition temperature	°C	min 225	595	590
Ignition air/ fuel ratio range "Lambda"	[-]	14.7	17.2	34.3
Laminar flame speed	cm/s	40	42	230

Figure 2: Hydrogen properties

Hydrogen is much less dense compared to diesel or methane. This single property exposes the first main weakness of hydrogen. Even with a very good energy content per unit of mass, the low density results in a low energy density. The pressurization or liquefaction of hydrogen improves this property but does not match that of diesel. Regarding thermodynamic properties however, hydrogen has interesting properties. The high flame speed, wide flammability range and the low ignition energy is auspicious for a good combustion. The wider range of flammability also offers the possibility to operate the engine with ultra-lean combustion. This opens the door to NOx emission reduction to very low level. However, ultra-lean operation requires several modifications to the engine architecture such as air and fuel path configuration.

2 Introduction to application in off-road sectors (working conditions & load profile)

Liebherr powertrains find their way in several application of the Off-road sector. By powering earth-moving machinery, mobile cranes, mining equipment as well as trains or ships, the engines have to endure very challenging conditions. Robustness becomes key in offering a relevant product for customers. Some of the most notable conditions such powertrain has to endure are the following:

- **Temperature**; cold and hot conditions depending on the location
- **Altitude**; high altitude brings challenges such as less dense air.
- **Humidity**; high degrees of humidity can impact the operation of the system
- **Vibration**; heavy-duty machinery is prone to shocks and vibrations
- **Endurance**; powertrains in such applications are expected to last
- **Load**; high transient performances have to be covered

From the listed challenges, emphasis can be set on the load. An engine has to cover the operation of a machine or sometimes, of several different machines. The flexibility of the diesel ICE is a strength that allowed standardization and reduced costs. The hydrogen ICE must retain this philosophy for the off-road sector. Following figure illustrates several Liebherr vehicles and their related operating characteristics

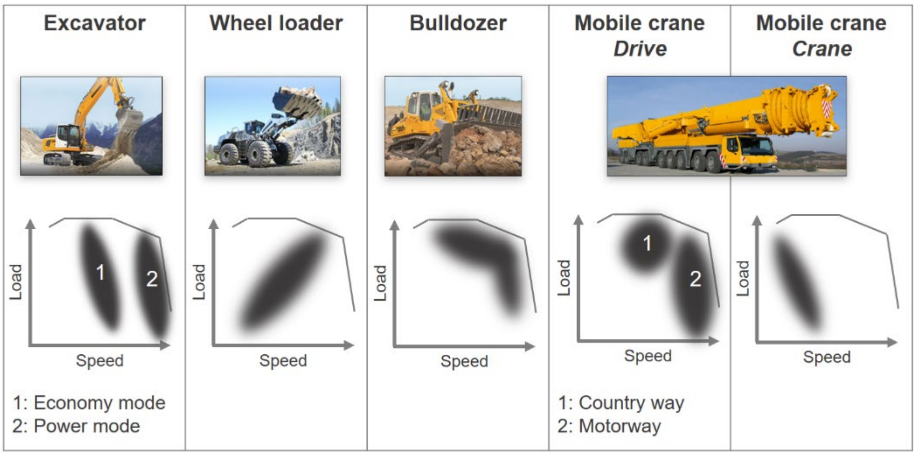

Figure 3: Operating cycles of Liebherr vehicles

3 Engine platform for hydrogen combustion engines

Liebherr benefits from decades of experience in the development and manufacturing of combustion engines. Liebherr's state-of-the-art diesel engines are a concentrate of all the earned experience. The hydrogen combustion engines carry over the latest D96 diesel platform, which is used in a variety of application in the Off-road sector. The development consists in the conversion of both the D964 9L and D966 13,5L to hydrogen combustion engines. The use of well-known platforms leads to reduced development complexity and costs. The new engines receive the denomination H964 and H966.

Figure 4: Diesel and hydrogen engine

The following table summarizes the main specifications of the H964 engine. Dimensions remain identical to those of the D964. Compression ratios are set as variables in order to perform the optimization of the main performance indicators such as efficiency and power density.

Parameter	Value
Engine Type	H964
Engine Displacement	9L
Engine Bore	135mm
Engine Stroke	157mm
Compression ratio	11-13

Figure 5:Engine characteristics

The air path of the engine relies on a dedicated double stage charging. The main driver of using the double stage configuration is to ensure an ultra-lean combustion, which leads to lower NOx emissions. The power density also increases, as leaner conditions limit the knocking region effect. An additional configuration based on a single stage charging combined with EGR is under investigation to evaluate its potential.

The fuel path of the diesel engine is specific to the management of liquid diesel fuel. The development of the hydrogen combustion engine therefore requires a fuel system redesign.

4 Engine architecture (DI + DF)

The engine architectures for the DI and the DF systems respectively follow the layout shown in the following figure. The DI configuration characterizes itself by the injection of the hydrogen directly inside the combustion chamber. A spark plug then triggers the fuel ignition. The DF configuration characterizes itself by the use of a pilot fuel to ignite the hydrogen. In the presented solution, the hydrogen injection happens in the intake port while the pilot fuel injection takes place directly inside the combustion chamber. The pilot fuel then ignites by means of compression ignition.

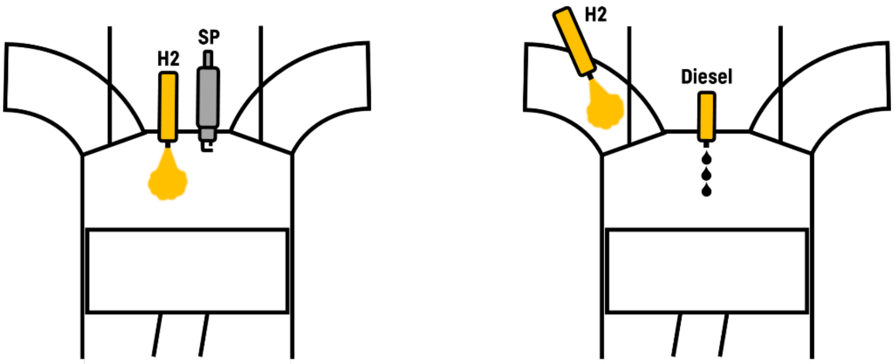

Figure 6:Engine configurations: DI : Direct injection and DF :Dual Fuel

The two architectures therefore differ one from another according to the following characteristics:

- Location of the hydrogen injection
- Method of ignition of the hydrogen

Following figures display a general view of the engines, their fuel paths and their air paths. Both configurations display a double stage charging to ensure sufficient airflow and pressure to achieve the ultra-lean conditions. The single stage configuration with EGR is an alternative solution under investigation. This less complex and more compact solution could also be a relevant step towards ultra-low NOx emission.

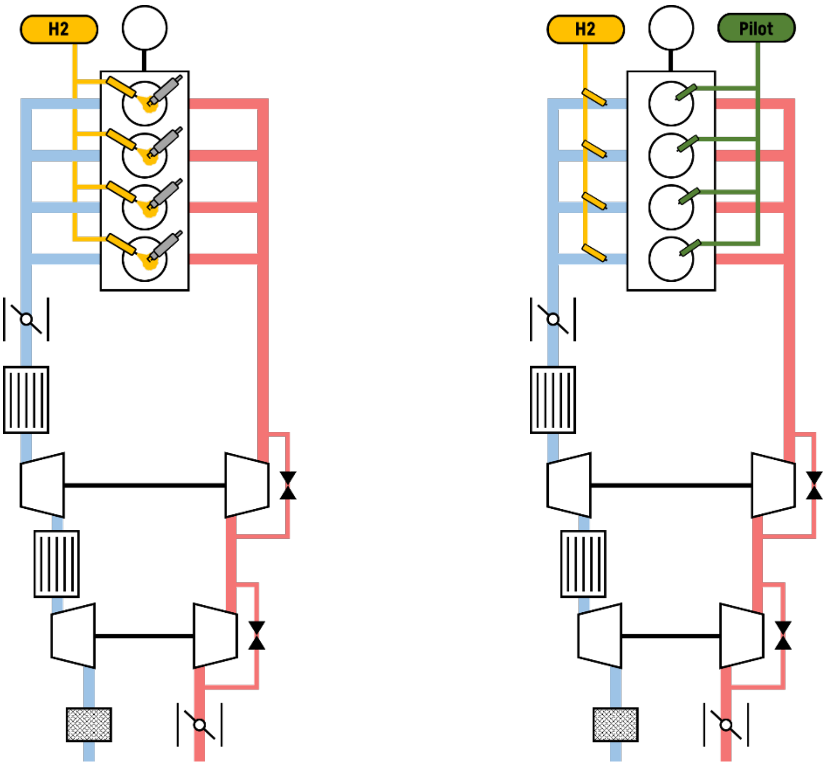

Figure 7: Engine architecture

4 Advantages and disadvantages of each technology

The direct injection hydrogen engine is obviously a strong competitor, as it is a ZEP. Carbon emissions are no longer a concern. Regarding the current targets, this would be the perfect solution. However, it suffers from the main downsides shared across most hydrogen engines, namely the poor energy density of hydrogen and its storage systems. Other downsides specific to the DI configuration are the need of a spark plug, which requires recurrent maintenance, and the need of a throttle body. Due to its configuration, the DI engine faces a challenge regarding the combustion stability. The test results discussed in the next section illustrate this phenomenon.

The Dual Fuel configuration for the hydrogen engine enables the ignition of the hydrogen by means of a compression ignited pilot fuel. This technology erases the need of a spark plug, simplifying the cylinder head and reducing maintenance. When using pilot ignition, the pilot fuel provides part of the energy. Combining hydrogen with diesel increases the overall energy density of the system compared to hydrogen. It becomes possible to offer systems that are more compact or that can run for longer on a single tank:

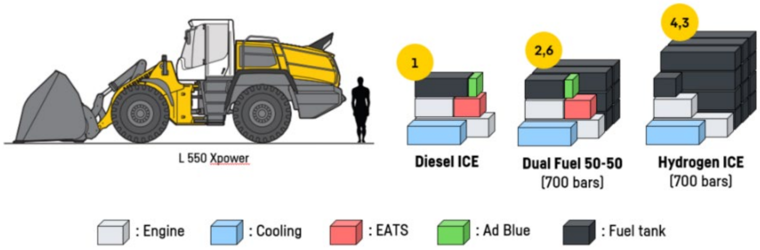

Figure 8: Power train sizes

Managing two different fuels is the main technical challenge of the Dual Fuel system. A specific fuel system is required for each fuel, from the tank all the way down to the fuel injector. The complexity is therefore greater by some margin. The complexity further increases with the need of an exhaust after-treatment system to manage the diesel specific emissions. This leads to the main environmental challenge of the DF system: managing the emissions. However, it is difficult to pick a side on this challenge, as it can be a benefit as

	unit	Diesel	H2	Dual Fuel*
NRTC CO2	[g/kWh]	734	< 1	87
Complete CO2	[g/kWh]	812	225	299

Renewable scenario :
45 g_{CO_2}/kWh$_{power}$

Hydrogen WTT : 2250 g_{CO_2}/kg
Diesel WTT : 342 g_{CO_2}/kg

	unit	HVO	H2	Dual Fuel*
NRTC CO2	[g/kWh]	734	< 1	87
Complete CO2	[g/kWh]	52	225	205

Renewable scenario :
45 g_{CO_2}/kWh$_{power}$

Hydrogen WTT : 2250 g_{CO_2}/kg
HVO WTT : -2956 g_{CO_2}/kg

Figure 9: CO2 emission using NRTC cycles

well as a downside depending on the conditions. The exhaust emissions increase when using diesel or HVO but not the Well-to-Wheel emissions:

The DF system reduces the emissions compared to a traditional diesel engine thanks to the hydrogen while keeping a good energy density compared to hydrogen. However, other fuels like HVO can even reduce emissions compared to the hydrogen engine. This obviously requires the fuel to be available but the DF engine presents itself as a flexible solution that has a good low emission potential.

Both air path configurations suggested also imply specific benefits and downsides. The double stage configuration enables the engine to function with higher boost pressures, opening the door to leaner mixtures and a potential NOx emission reduction. The greater air excess also reduces the sensitivity to knock. The main downside of this configuration is its complexity. The need of two turbochargers and one interstage-cooler results in a less compact engine. The single stage with EGR configuration is more compact and can be a good alternative for NOx emission control. The risk of water condensation and the operation of the EGR valve in the transient phase are the main challenges of the system.

8 Results and Discussion

This section presents the results of the test campaign conducted in Bulle, Switzerland. Direct injection and dual fuel multi-cylinder engines has been investigated in our testing facilities. Both engine use the same air path architecture (turbocharger and cooler).

8.1 Static measurement

The dual fuel engine show a better combustion stability than the DI engine. The evaluation of the combustion stability has been performed using the analysis of the coefficient of variation in IMEP or covariance of IMEP "COV". The calculation of these parameters is performed over 100 cycles.
At 1900 rpm and 13 bar of BMEP, the DF demonstrates a better stability (< 1.2 Bar) than DI (< 1.9 bar). This can also be identified on the corresponding pressure trace:

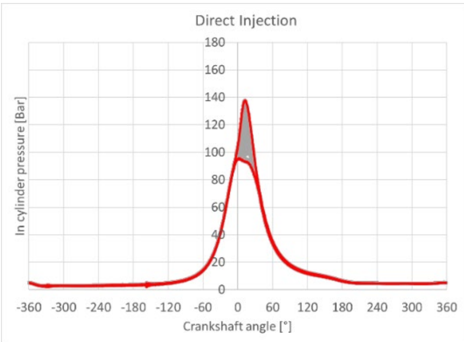

Figure 11: Cylinder pressure DI

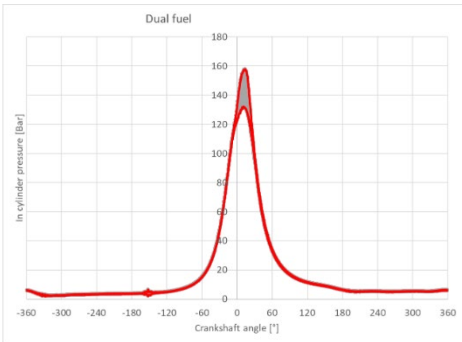

Figure 10: Cylinder pressure DF

The DI engine uses a spark plug to start the combustion. Flame propagation is therefore strongly dependent of the turbulence and the mixing quality in the combustion chamber. Those two parameters have a strong cycle-to-cycle variability, which is the variability of IMEP. This instability can be improved by lowering the lambda (equivalent air-fuel ratio), but in this case the tradeoff is a strong NOx emissions increase.

The dual fuel engine combustion looks more like a diesel combustion. The diesel spray aerodynamic has the greatest impact on the flame speed. A precise control of the diesel injection parameters (pressure, SOI) easily ensures less cycle-to-cycle variability. The burning diesel then ignites the hydrogen. However, the injection mass fraction of diesel (compared to overall hydrogen mass) has to be large enough to guarantee this effect (in our example this can reach 10 % until16%). This effect, coupled with a higher compression ratio, improves the combustion speed (CA10 - CA90) of ~ 30 compared to hydrogen engine, even though the DF runs with a leaner configuration.
In order to maximize the quality of mixing the SOI of DI engine has been set early. This leads to a decrease in volumetric efficiency, the DF engine operating with a PFI configuration (Hydrogen port fuel injection) has a lower value in terms of volumetric efficiency. This PFI configuration promote a low NOx emissions due to better mixing behaviour.
In theory, the DF engine must have a better efficiency than the DI engine. This is due to : a quicker combustion speed; a leaner combustion, which reduces the heat transfer from gas to coolant during combustion; a CA50 that is earlier in the DF engine.
However, we measure only a slight improvement of efficiency for the DF compared to the DI engine. The main explanation to this occurrence is the mechanical power consumption of the diesel high-pressure pump. Based on component measurement, the pump drops the engine efficiency in a somehow a dominant ratio at this operating point.
The hydrogen consumption of the DF is lower by around 10 % at this operating point compared to the DI, which allows a reduction of the H2 tank volume. The potential of tank size reduction is even larger by adjusting the diesel quantity according to the load level of the vehicle.
Additionally, the power density can further be improved by increasing the diesel mass fraction. However, NOx emissions (at this operating point 3.8 g/kWh) and CO2 emissions will increase due to the part of diesel combustion. The NOx emissions can be solved by a simple exhaust after treatment system, the CO2 emission issue can be handled only by using alternative fuel such as HVO. Even with this configuration in DF using a diesel pilot, the potential of CO2 emission reduction is higher and around 92 % compared normal diesel operating mode.

8.2 Emissions using NRTC cycle

Both engines have been tested using NRTC cycles. The following results illustrate the emissions values regarding NOx and CO2 - emission for hot NRTC at engine out (without after-treatment system), the measurement has been performed for the same engine power level.

	NOX [g/kWh]	CO2 [g/kWh]
Dual fuel	3.3	43
Direct injection	< 0.7	< 0.5

Current EU Stage V regulations limitation regarding the NOx emission is 0.4g/kWh. Therefore, a small after-treatment system is mandatory for the DF engine. The DI engine a lower NOx emission in NRTC cycle compared to dual fuel. This will lead to even operation with a simpler and cheaper concept of EATS or without EATS for a certain engine configuration. The dual fuel engine can satisfy the requirement of Low Emission Vehicle "LEV regarding CO2 emission"; however, the zero emissions requirement can be achieved only with 100 % fuel engine.

8.3 Dynamic performance

The following graphic shows the dynamic response to a load step at constant speed for diesel and DF engine:

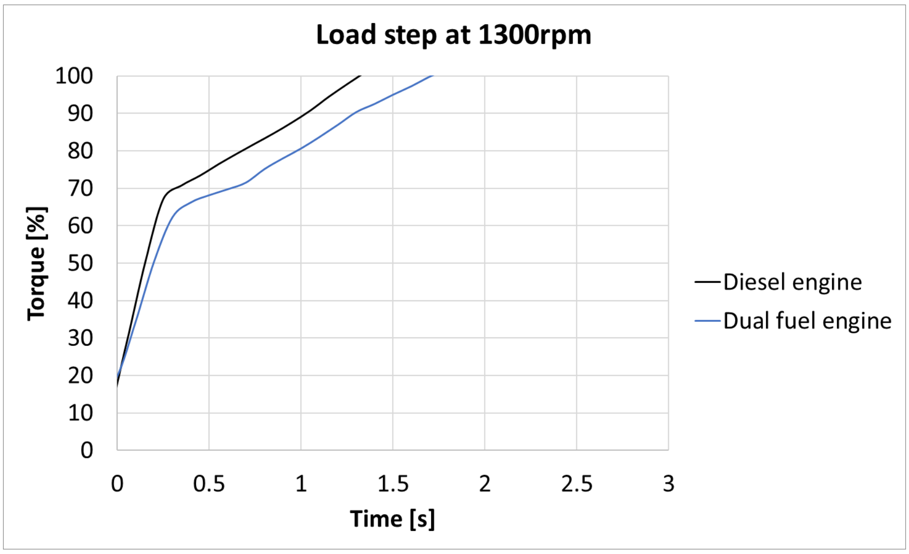

Figure 12:Engine dynamic for diesel and DF

The hydrogen ICE with DF configuration has a potential to improve the engine dynamics by increasing the diesel or HVO fuel quantity. This increase of fuel quantity should only occur in transient phase (during torque increase). After reaching the targeted torque, the controller switches to the normal mode by injecting a smaller quantity required for pilot injection, which is calibrated for a stable combustion. We considered several strategies, such as limiting the NOx emission or respecting the CO2 emissions for "LEV" "Low Emissions Regulation" in this investigation.
Pure hydrogen combustion ignited by spark plug results in slightly lower dynamic, result of the knock-limitation in the enrichment zone. This effect "knock limit" can be improved in the case of dual fuel engine by increasing the quantity of the diesel injected mass.

9 Summary and conclusion

The CO2 emission reduction target will affect all sectors in the future. The Off-Road sector will also introduce several CO2-neutral powertrains in order to achieve this target. It is likely that the future accounting method will consider at least the "Well to Wheel" approach. This promote the introduction of global CO2 neutral and renewable fuels in addition to local "Tank to wheel" ZE- fuel such as hydrogen or ammonia in ICEs.
One way of following this strategy is to use green energy to produce hydrogen and design a

CO_2 neutral powertrain based on the hydrogen combustion engines. Hydrogen combustion engines have been the subject of many investigations. However, recently the combustion engine based on hydrogen fuel has gained a strong acceptance by several OEM. This is due to the maturity, robustness, cost and investment (use of the existing components of the combustion engine, drive kits and vehicle architectures), mainenance as well as favorable “Total Cost of Ownership” (TCO) compared to others zero emission (ZE) technologies. In General, the H_2 combustion engine is, from a technical and commercial point of view, one of the suitable solutions for the future CO_2 neutral power train.
The result of this study shows that the 100% hydrogen fueled engine with double stage configuration can achieve required efficiency with low NO_x engine out emission compared to dual fuel engine. The H2-ICE could operate without or with a simplified EATS unit and is easy to integrate in the current vehicle infrastructures and can operate in applications with hard operating -conditions.
The duel fuel engine has an advantage of higher flexibility in terms of engine management in transient phase. Furthermore, the dual fuel engine offers the possibility to reduce the overall tank size (hydrogen & diesel) and operating the engine with two different modes depending on the required regulation in the operating zones.

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