Lube oil formulation as a lever to mitigate combustion anomalies in Liebherr off-highway hydrogen fueled ICE

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Liebherr International



Factsheet: Group overview (2025)



1949

Founded by Hans Liebherr in Kirchdorf an der Iller, Germany

Parent company
Liebherr-International AG based in Bulle, Switzerland

Liebherr is a family-run technology company

13 Product segments

55,963

Employees

>40

Production sites

14,772

Revenue in € m

>150

Companies

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Liebherr Machines Bulle SA in Switzerland



Bulle

Switzerland

1978

Foundation

1.400

Employees

188.100 m²

Total area

Product portfolio

— Diesel and gas engines
— Hydraulic pumps and -engines
— Splitter box

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Liebherr H_2 Internal Combustion Engine (ICE) technology

Hydrogen is one of the key enabler in the roadmap to achieving net-zero emission powertrains. However, replacing a diesel engine in today's construction machinery poses some significant challenges.

H_2 ICE advantages for Liebherr off-road applications:

- ✓ Nearly **CO_2 free** solution
- ✓ High **power density** (215kW/ton for engine only) compared to battery electric vehicle
- ✓ Excellent **transient performances**
- ✓ **Low hydrogen purity** requirement
- ✓ Not sensitive to **vibrations** like fuel cells
- ✓ Does not emit **liquid water** like fuel cells
- ✓ **Cost** competitive
- ✓ Existing **cooling package** on machine
- ✓ Existing **after-sale** and **remanufacturing** infrastructure



Liebherr H_2 ICE development history

2019

December 2019: 1st 6 cylinders

2020

December 2020:

- 1st start of 6 cylinders at IAV Gifhorn in Germany
- Base calibration for transient

2021

September 2021:

- 1st start of hydrogen test cells at Liebherr Machine Bulle in Switzerland
- Commissioning of R9XX H2 hydrogen excavator

2022



Launch of 4-cylinders development for wheel loader machine

October 2022: BAUMA innovation award



2023

May 2024: 1st start of H2 ICE on Liebherr wheel loader



2024



2025



November 2025: Start of field test in quarry in Austria

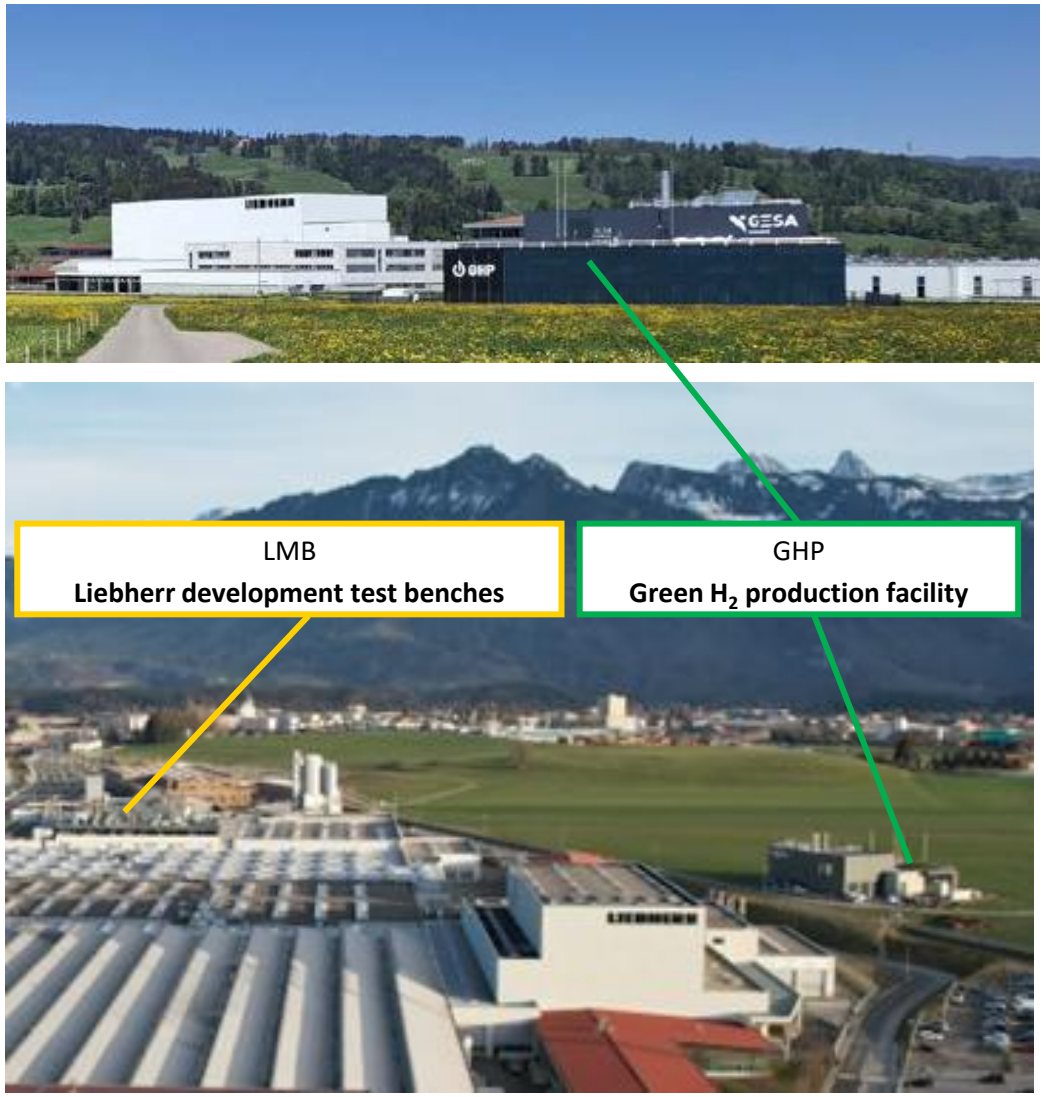
2026

2026: field test on-going

Liebherr H_2 ICE testing facility

- **Green hydrogen** production facility fully automated with **2 x 1MW electrolyzers** fed by renewable energy (biomass + hydraulic + solar). Max flow rate 40kg/h, high purity (99,9999%).
- 1 **storage system** with metallic hydrur (LaNi5) up to 30bar.
- 1 **compressor** up to 450 bar.
- **Pipeline** between production facility and test benches.
- 1 truck-trailer loading port for back-up.
- **2 development engine test benches** converted to hydrogen.





Liebherr H_2 ICE prototype specifications

Fuel	100% H_2
Configuration	In-line engine
Number of cylinders	4
Bore	135 mm
Stroke	157 mm
Displacement	9.0 l



H964 hydrogen engine | Liebherr - Liebherr

Liebherr H_2 ICE technology

Injection system	**Liebherr PFI system** with inlet pressure 25bar
Pistons	Steel with dedicated bowl shape and compression ratio. Specific ring package.
Camshaft	Dedicated **cam profiles** with reduced overlap
Turbocharging system	**2-stage turbochargers** with air-to-water coolers and electronic wastegate control
Intake manifold	Low volume intake manifold + intake throttle
Engine Control Unit	**Liebherr ECU** with software developed in-house
Spark ignition	Capacitive ignition controller with dedicated M14 iridium spark plugs and variable spark profile
Crankcase ventilation system	Passive closed system with filter element
Knock detection	2 x sensors mounted on block
Lube oil	**Specific lube oil** developed with external partner



H964 hydrogen engine | Liebherr - Liebherr

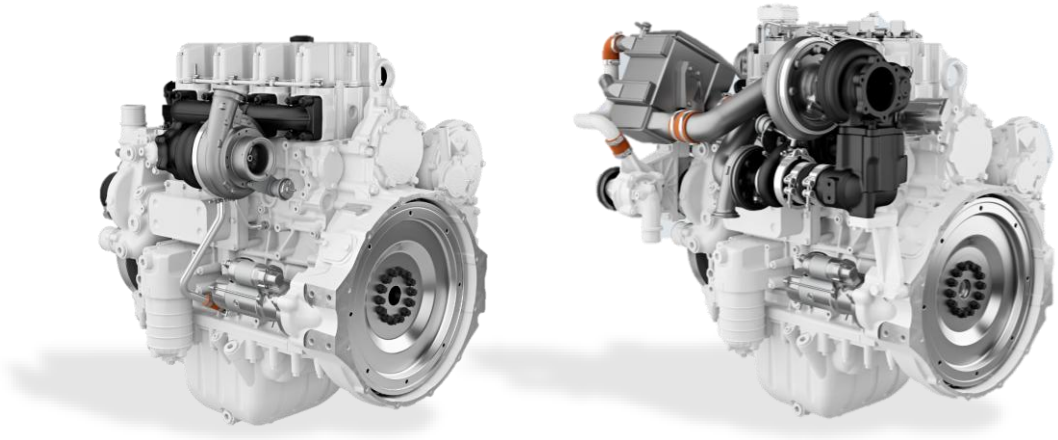


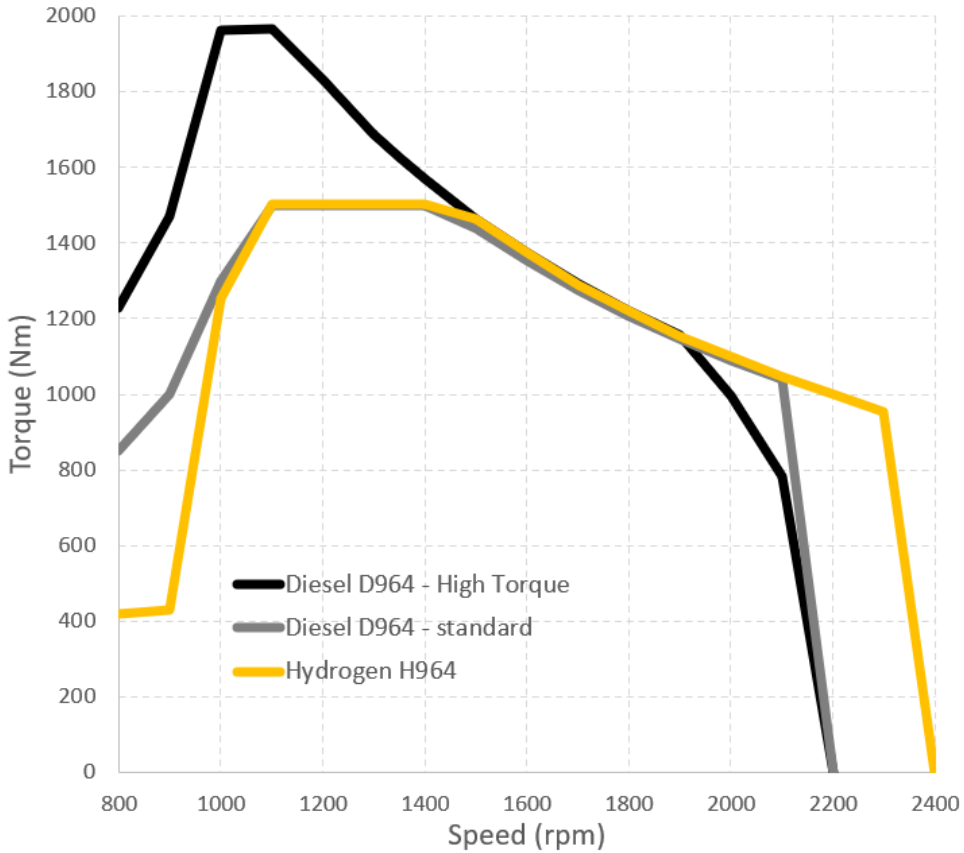
H964 hydrogen engine | Liebherr - Liebherr

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Liebherr H_2 ICE full load performance

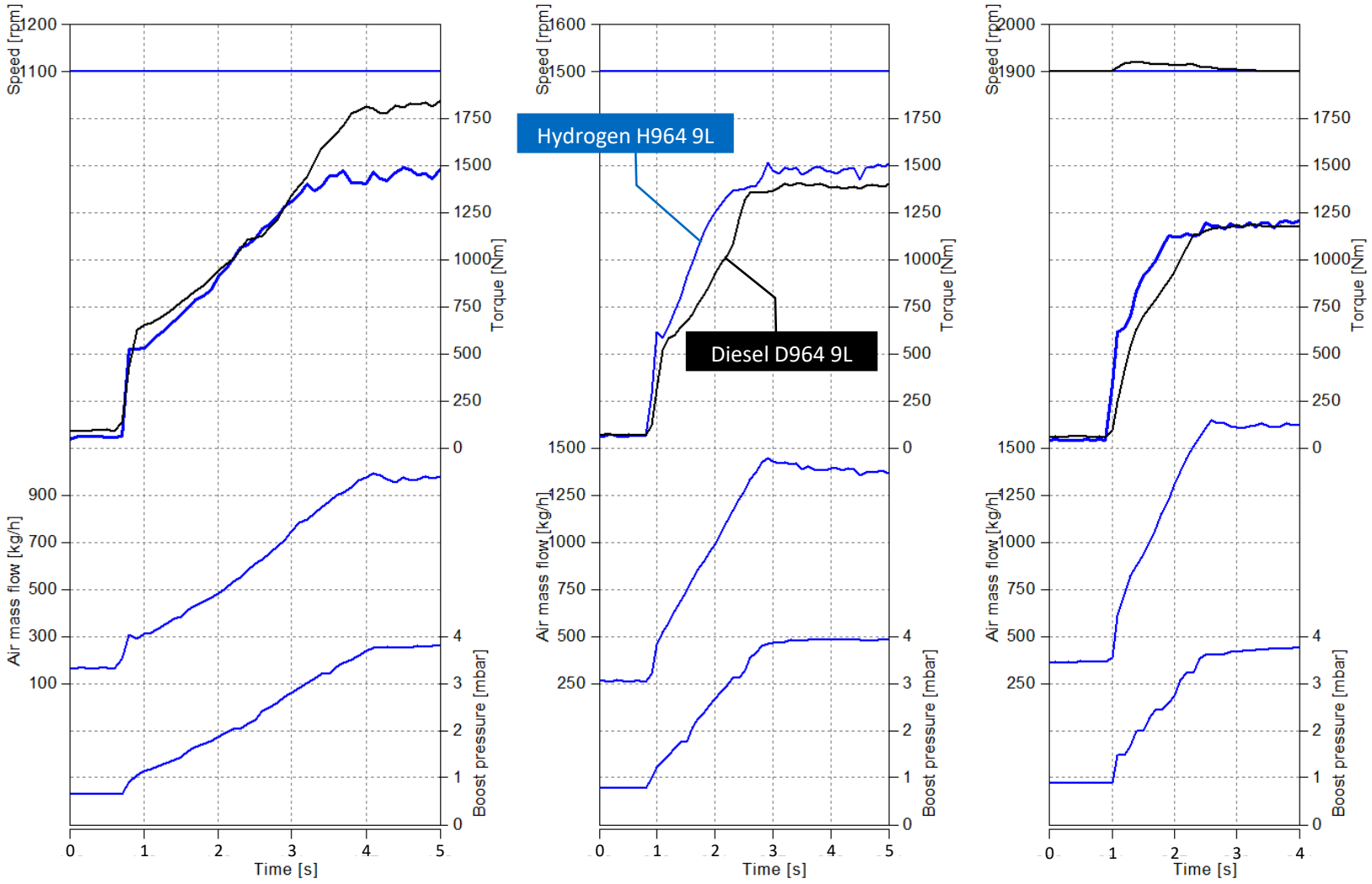
	Diesel D964	Hydrogen H964
Fuel	100% diesel	100% H_2
Cylinders	4	
Displacement	9 l	
Rated power	200kW – 230 kW	230kW
Maximum Torque	1500Nm – 1965Nm	1500Nm
Maximum BMEP	27,5b @ 1100rpm	21b @ 1100rpm-1400rpm





Liebherr H_2 ICE transient performance

Liebherr 4 cylinders H_2 ICE has **similar transient response as equivalent diesel ICE** thanks to high performance boosting system and innovative engine control system.



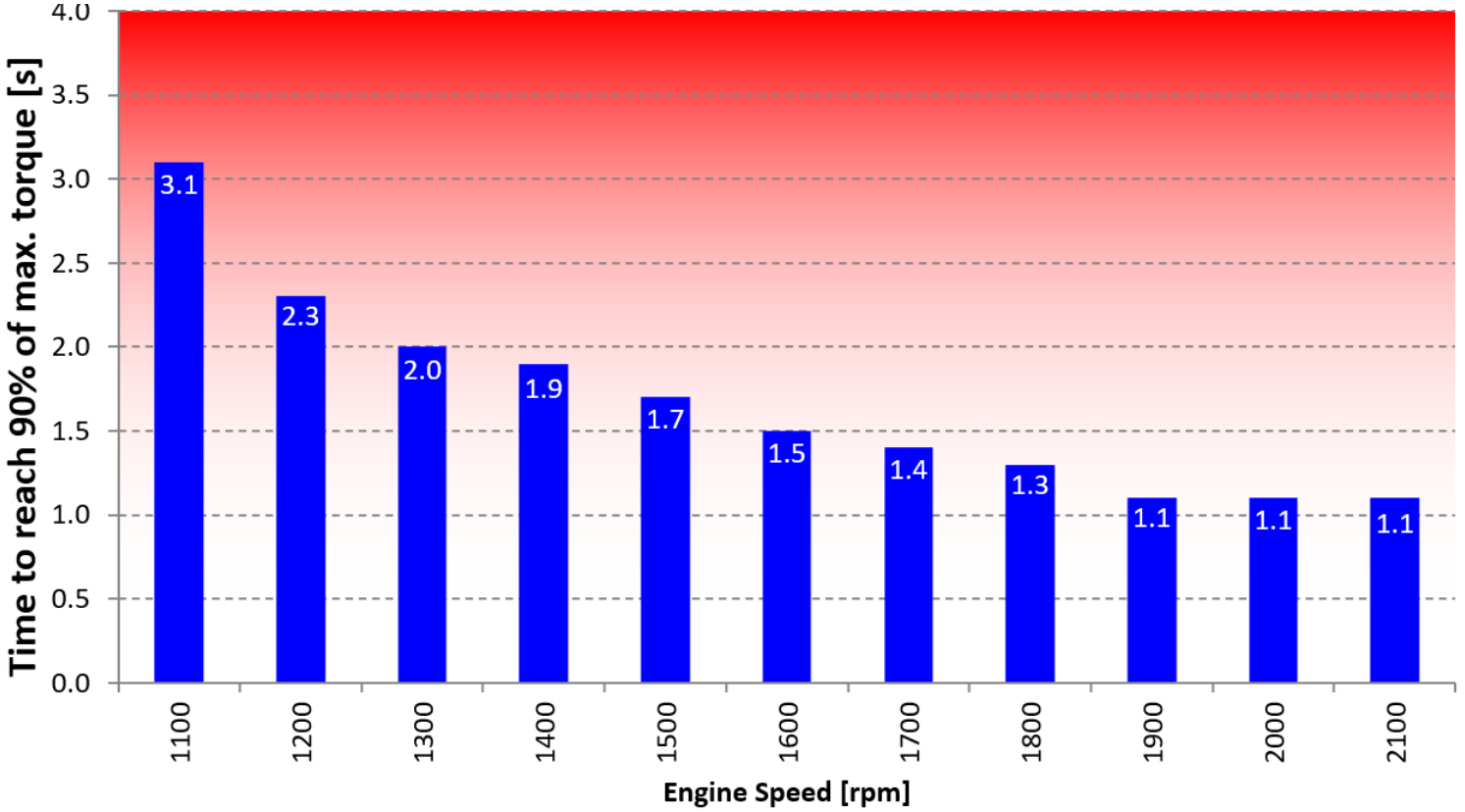
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Liebherr H_2 ICE transient performance



Time to reach 90% of maximum torque during load steps from 5% load at iso-speed.

These transient performances fulfill Liebherr off-road applications such as wheel loaders and excavators.



Application

Machine type	Liebherr wheel loader L566 H
Machine weight	26 tons
Payload	Up to 9 tons
H_2 storage system	3 carbon fiber tanks @ 700 bar 34 kg of usable H_2
H_2 pressure at engine inlet	25 bar
Cold start ability	-10°C to -15°C

Wheel loader is the **most transient application** from Liebherr machines portfolio.





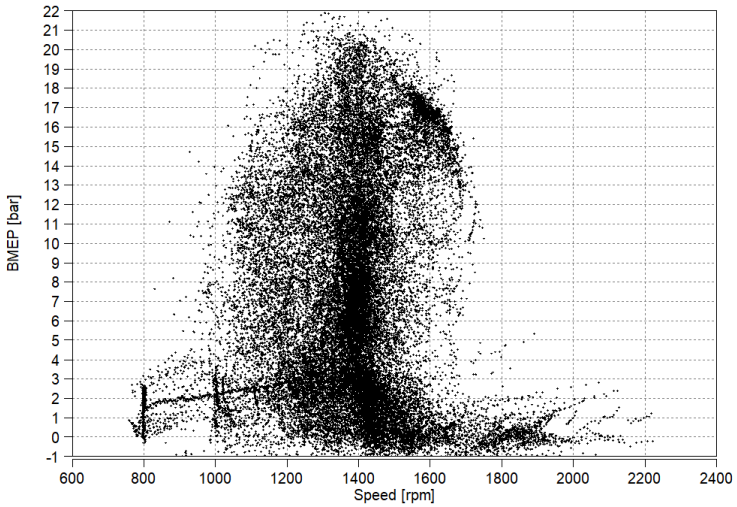


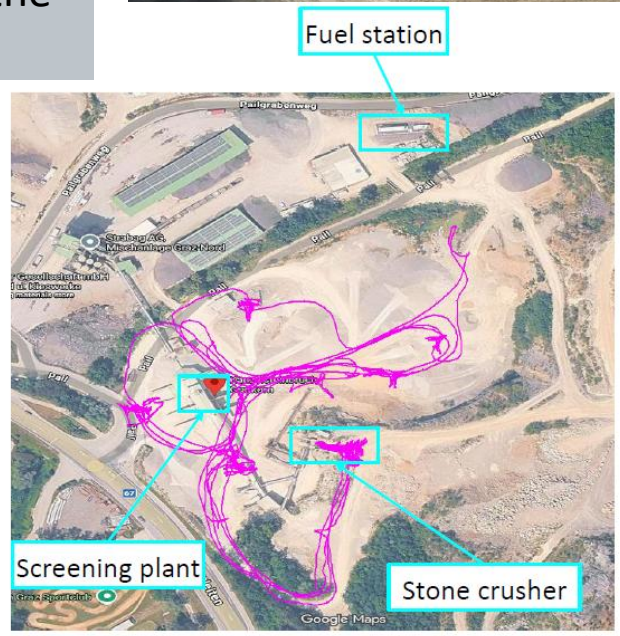
Field tests machine

Wheel loader machine with H_2 ICE is operated by customer Strabag in Austria under field test operation over a period of two years. It should save up to 100 tons of CO_2 each year, corresponding to about 37,500 liters of diesel.

A hydrogen filling station is built on-site to refuel the wheel loader at the quarry.





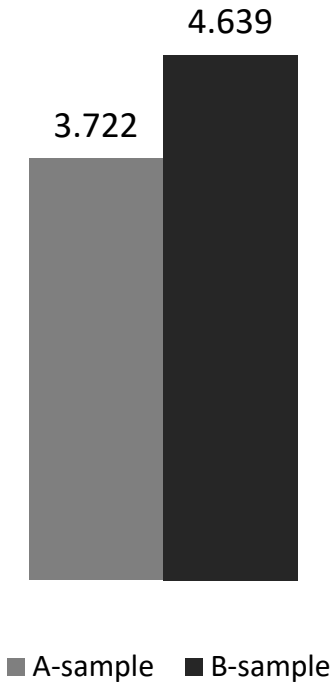




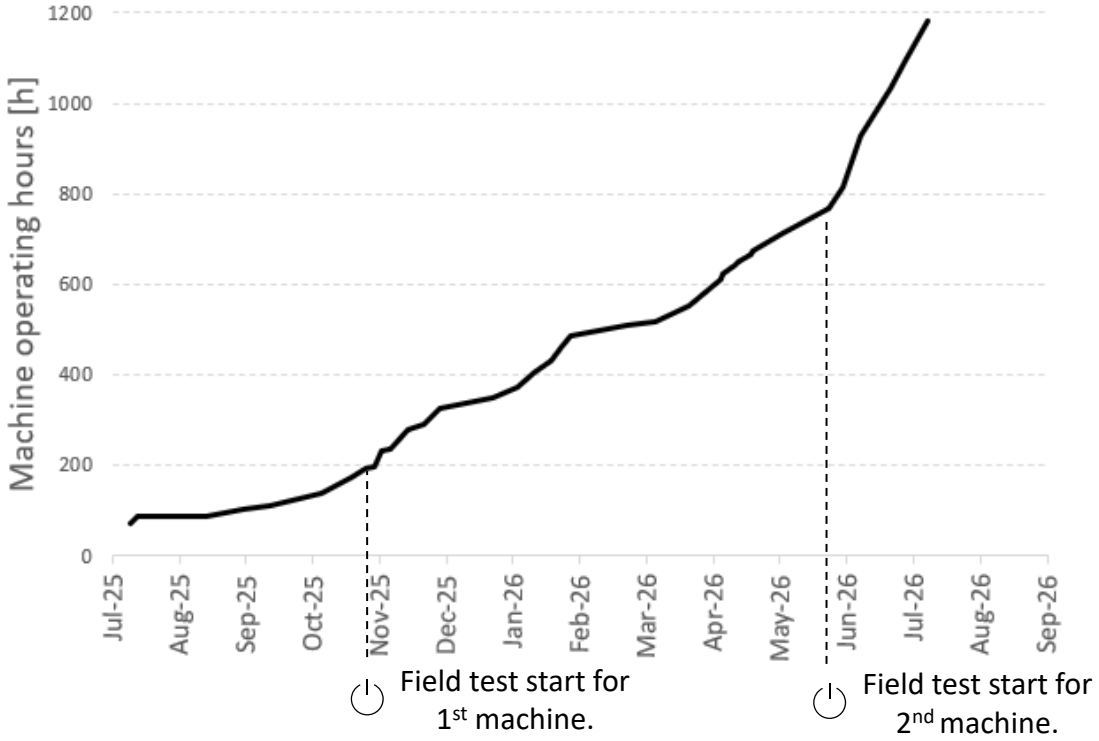
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Accumulated hours

8 361 hours accumulated on H964 **engine in test benches** at Liebherr Machine Bulle SA in Switzerland.



Already more than **1200 hours** accumulated on H964 engines in **field tests machines** in quarry in Austria.



New safety systems for H_2 ICE

Protections against **combustion anomalies**

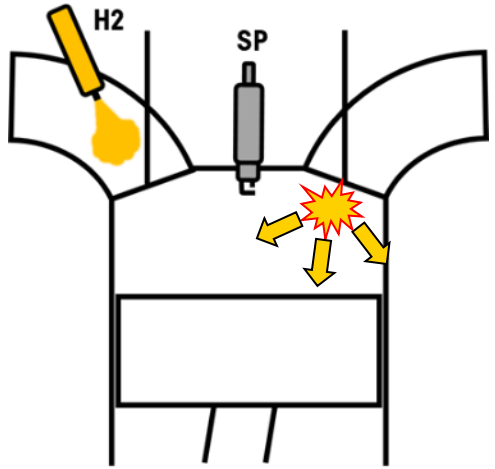
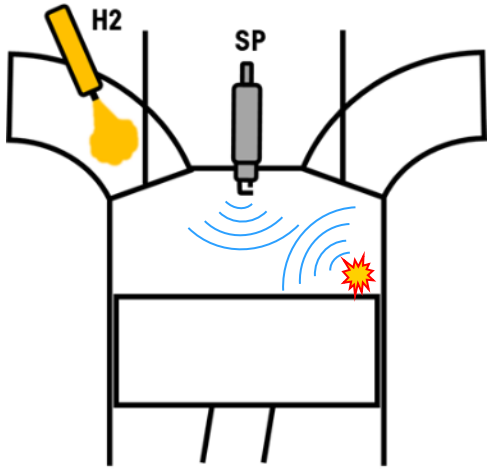
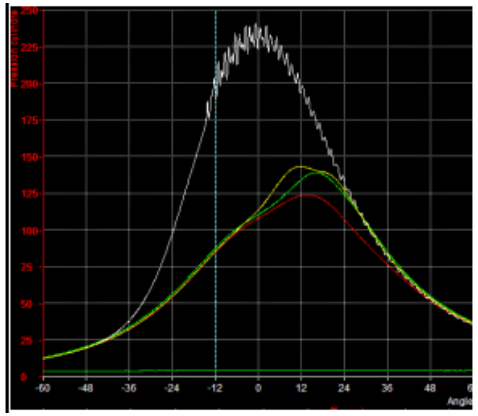
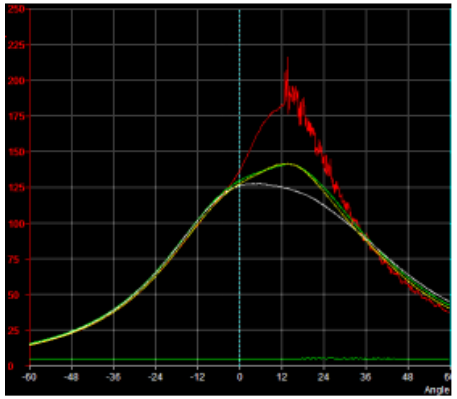
Injection system	☑ Check absence of fuel in the injection system at key-on ☑ Flushing before start ☑ Leak check at each start ☑ Permanent injectors monitoring ☑ Deactivation of H_2 supply after stop
Air path	☑ Flushing at engine stop ☑ Flushing sequence in case previous stop NOK
Knock control	☑ Knock detection ☑ Knock control
Backfire	☑ Backfire detection ☑ Backfire reaction
Misfire	☑ Misfire detection with faulty cylinder identification and misfire rate ☑ Misfire reaction
H_2 leakage detection	☑ Underhood H_2 sensor ☑ H_2 sensor in intake system
H_2 content in crankcase	☑ After 60 seconds at low idle and 2 minutes with engine stopped the H_2 content in crankcase is below lower explosive limit.
Machine	☑ Emergency switch ☑ Air compressor for maintenance activities

Focus on 2 types of combustion anomalies

2 types of combustion anomalies linked to high flammability of hydrogen, hot spots, residuals, electrical discharges and potential **spontaneous ignition of oil droplets**.

Potential sources **oil transportation to combustion chamber**:

1. Cylinder liners
2. Piston rings
3. Recirculated blow-by gas
4. Intake valve stem sealing
5. Turbochargers compressor sealing

Pre-ignition *Before spark*	**Knock** *After spark*
	
	

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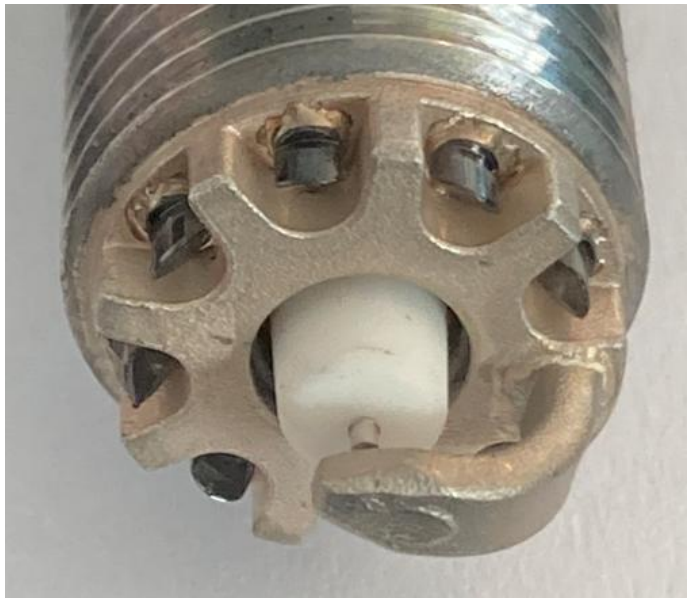
In-cylinder combustion anomalies visualization

Previous measurement performed on A-sample engine with specific instrumented spark plugs demonstrated that knock starts on the liner periphery.

Good indication that the combustion is affected by **oil transportation from liner** to combustion chamber and/or slower flame spread to intake valve side.

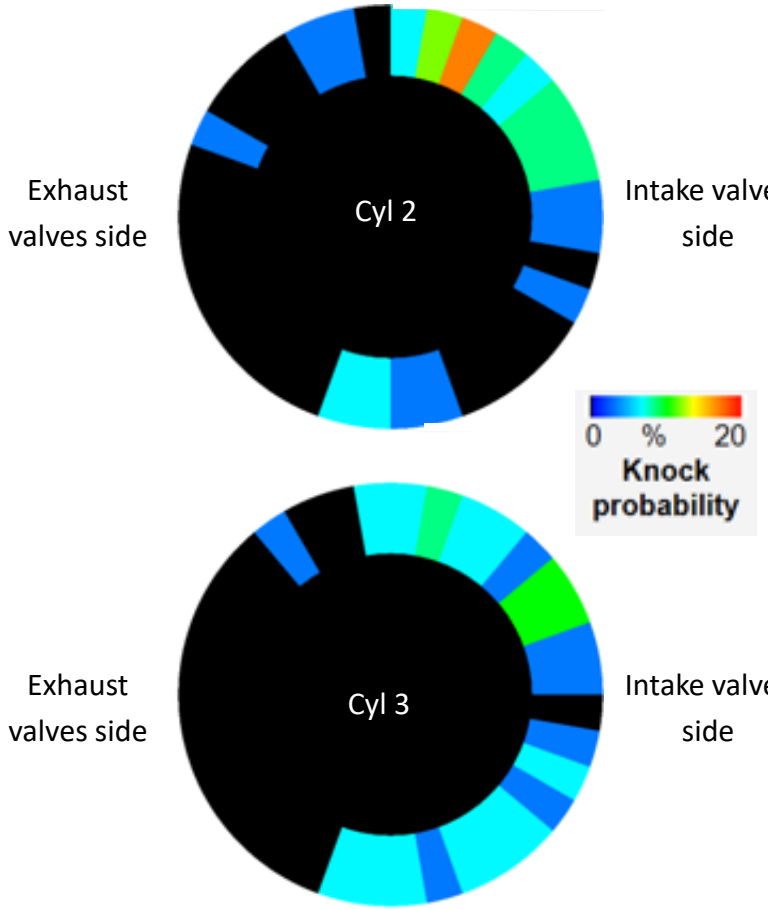






H964 A-sample engine

1900rpm/100%



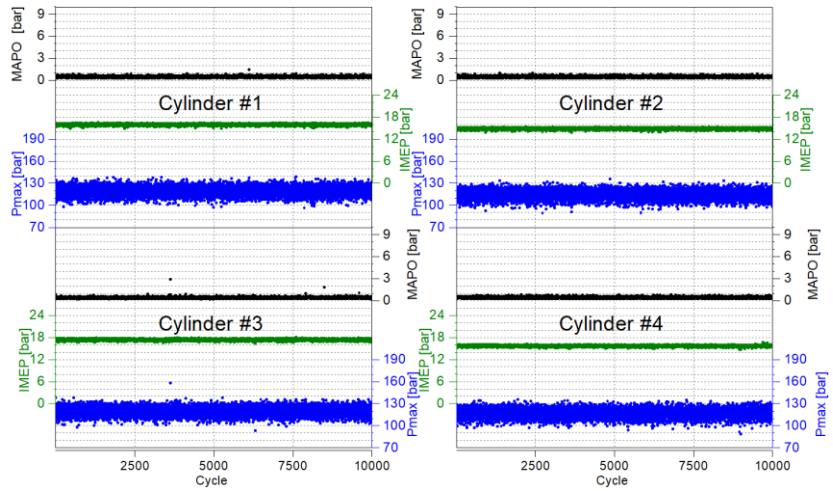
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Combustion anomalies measurement methodology

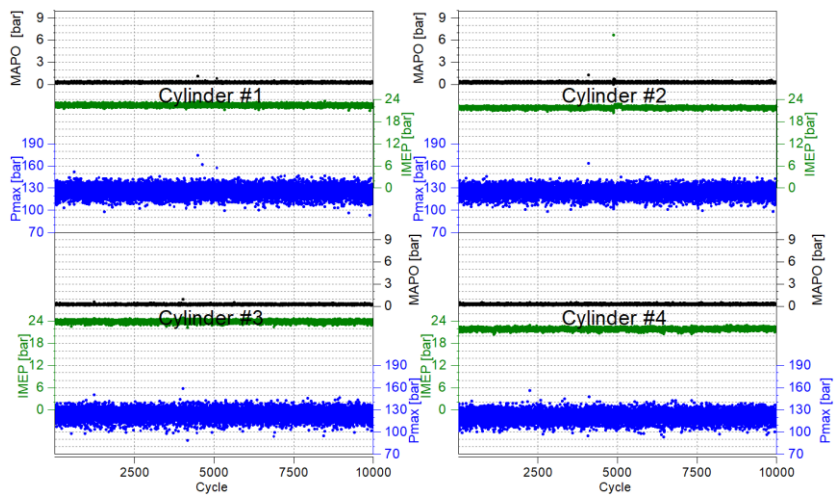
Steady-state measurement of combustion anomalies for 10’000 combustion cycles on each cylinder.

4 engine speeds in full load in nominal lab temperature: 25°C ambient.

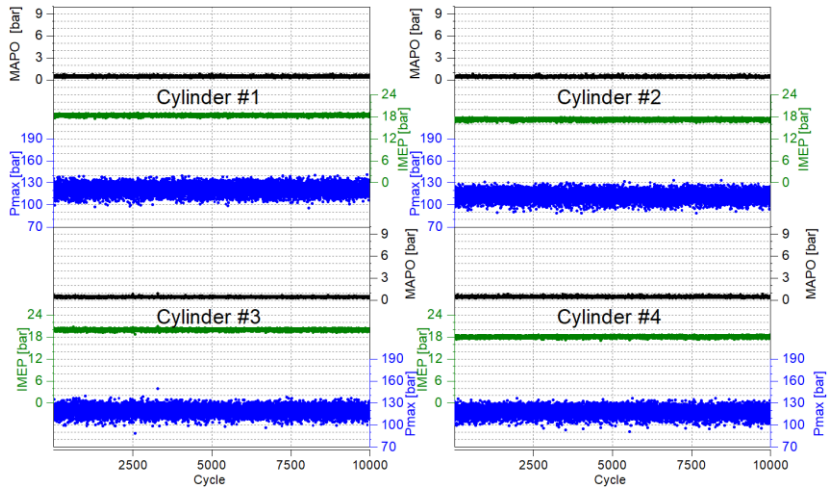
2300rpm – 13bBMEP – Reference oil & nominal temp



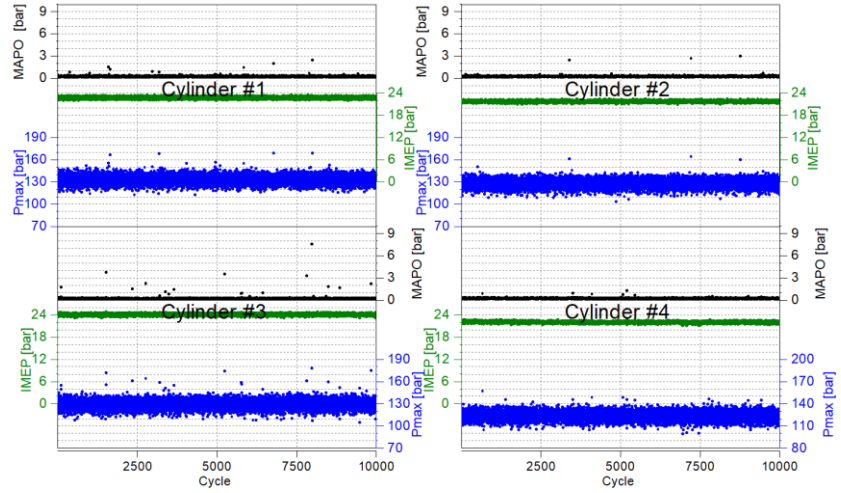
1500rpm – 21bBMEP – Reference oil & nominal temp



1900rpm – 16bBMEP – Reference oil & nominal temp



1100rpm – 12bBMEP – Reference oil & nominal temp

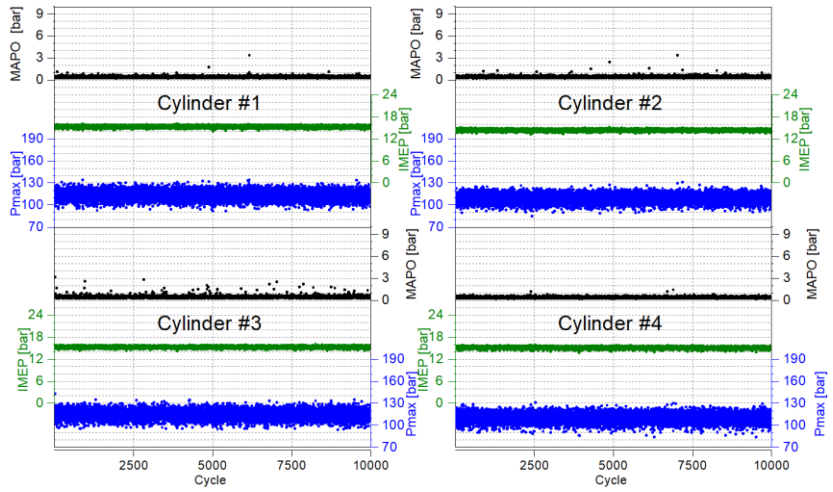


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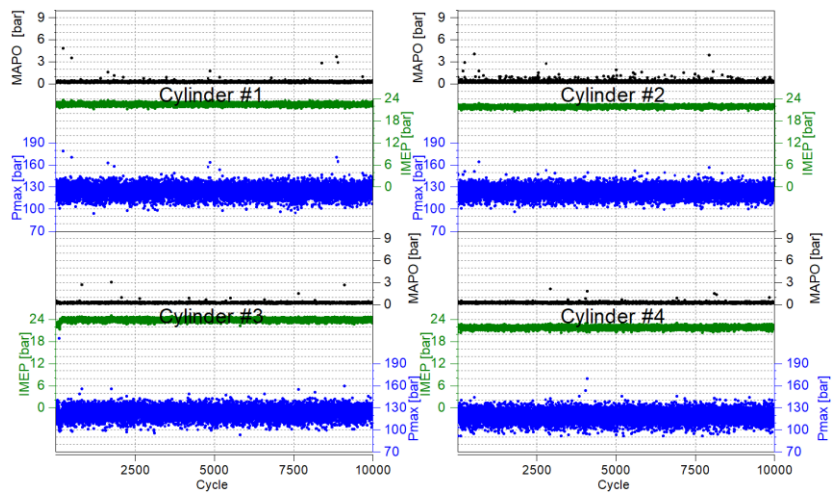
Combustion anomalies measurement methodology

Same measurement with **elevated temperatures** to simulate 40°C ambient temperature and create more combustion anomalies: intake air + manifold air + hydrogen are increased by +15K compared to nominal lab temperature.

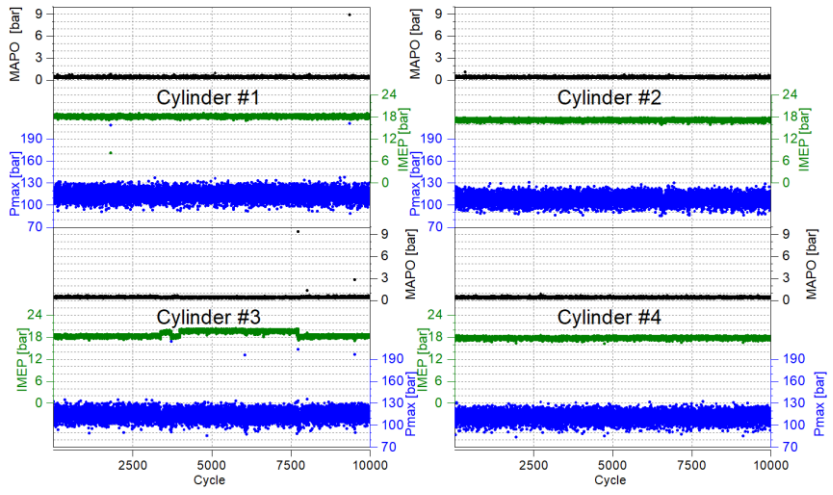
2300rpm – 13bBMEP – Reference oil & elevated temp



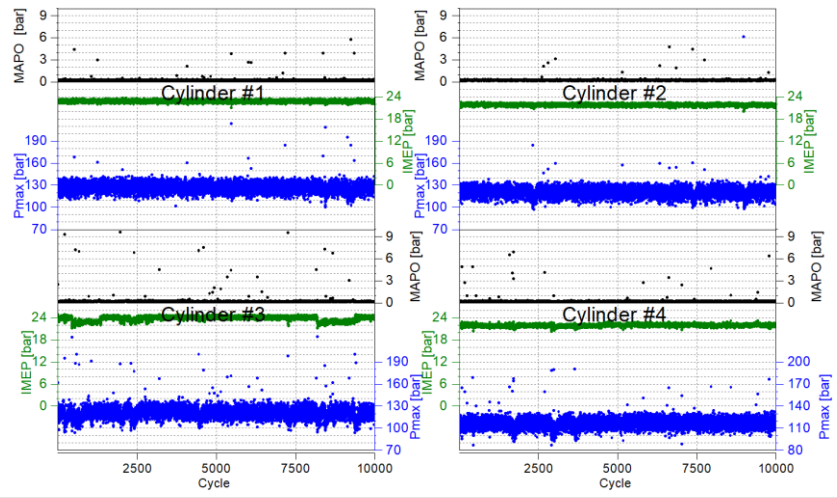
1500rpm – 21bBMEP – Reference oil & elevated temp



1900rpm – 16bBMEP – Reference oil & elevated temp



1100rpm – 21bBMEP – Reference oil & elevated temp

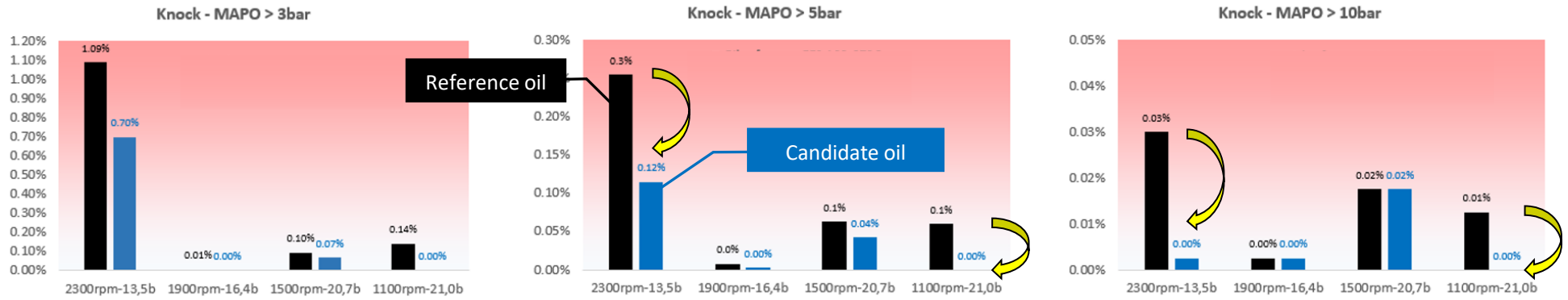


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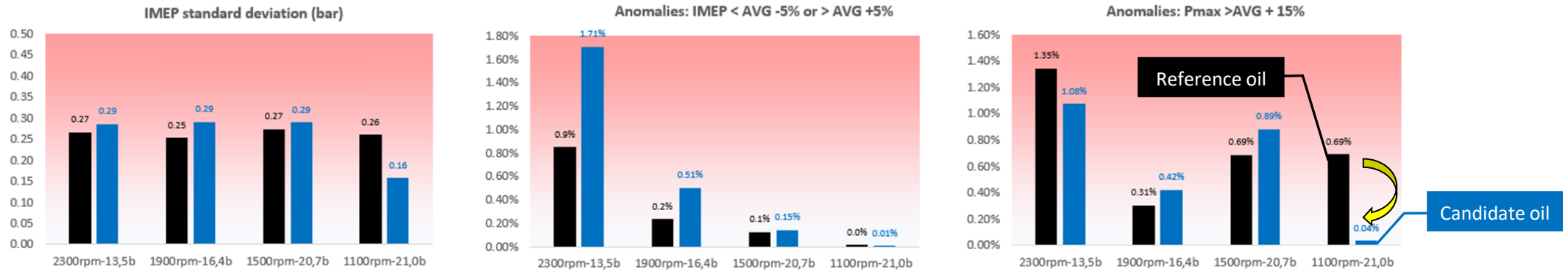
Combustion anomalies measurement methodology

Statistics of the 10’000 combustion cycles on each cylinder: total 40’000 combustion cycles.

- 3 different **knock intensities**



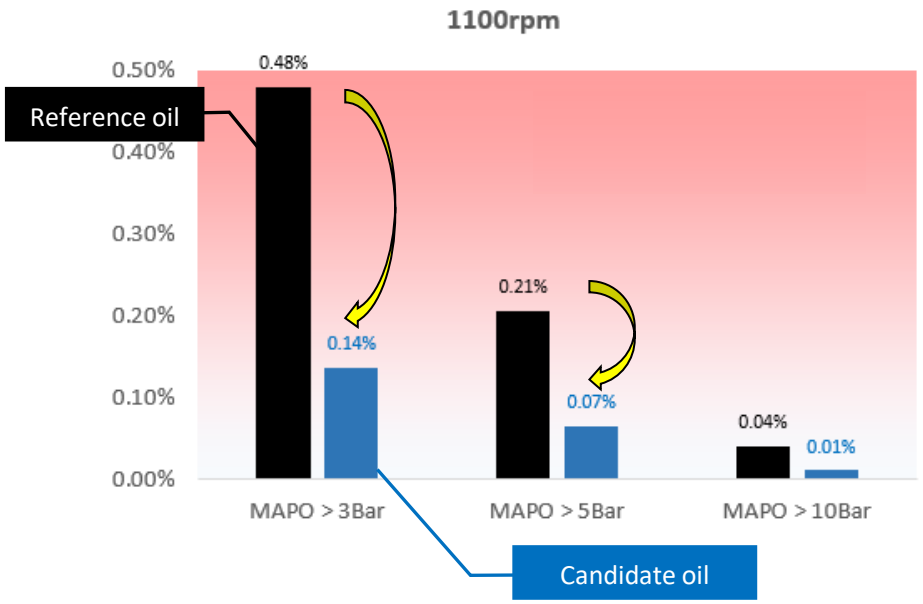
- **IMEP** standard deviation and deviation to average
- Excessive **peak cylinder pressures**

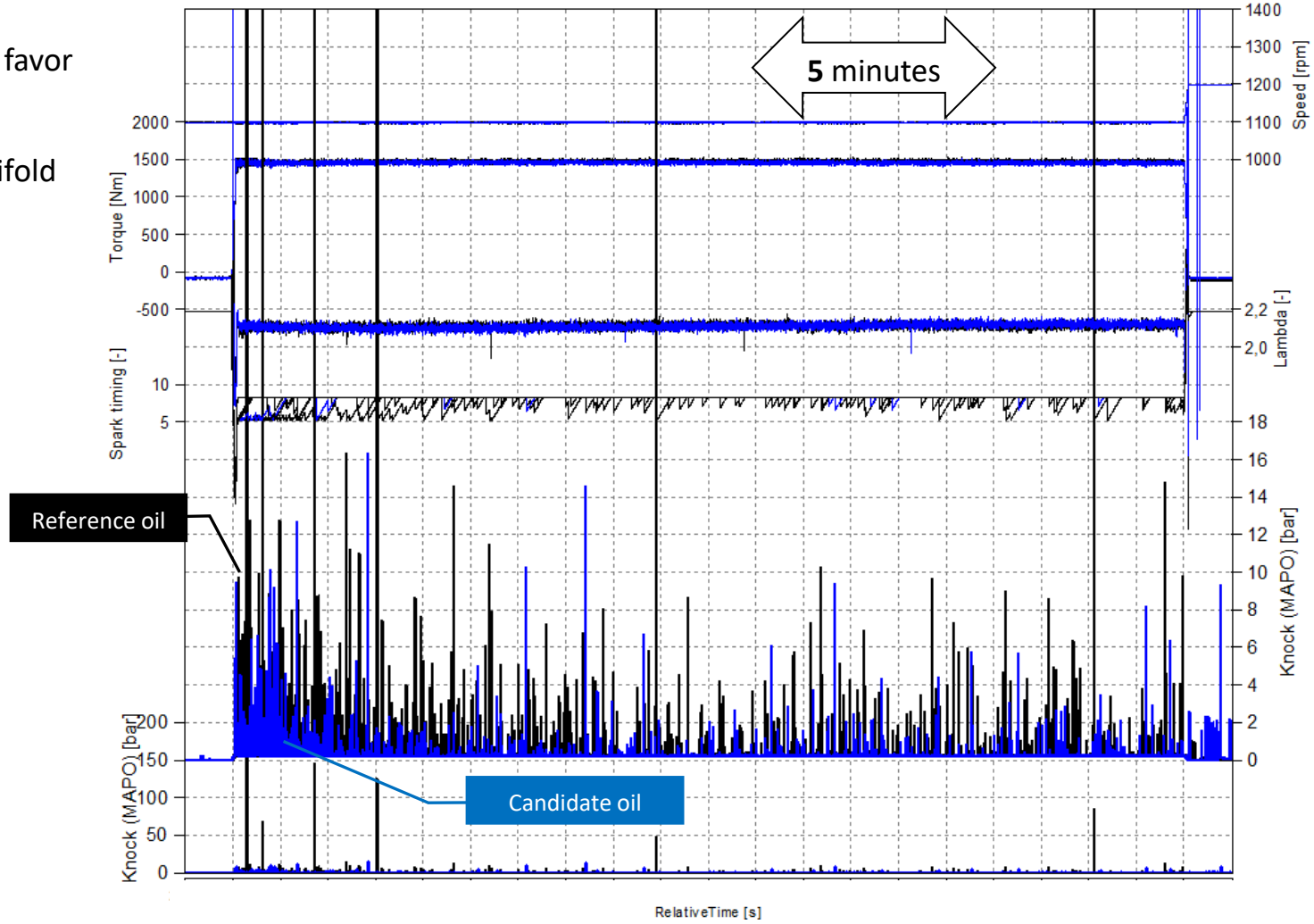


Combustion anomalies measurement methodology

Semi-transient measurement of combustion anomalies to favor oil transport to combustion chamber:

1. 1% load during 20 minutes with vacuum in intake manifold to accumulate oil inside combustion chamber.
2. Rapid load increase to full load.
3. Full load during 20 minutes.



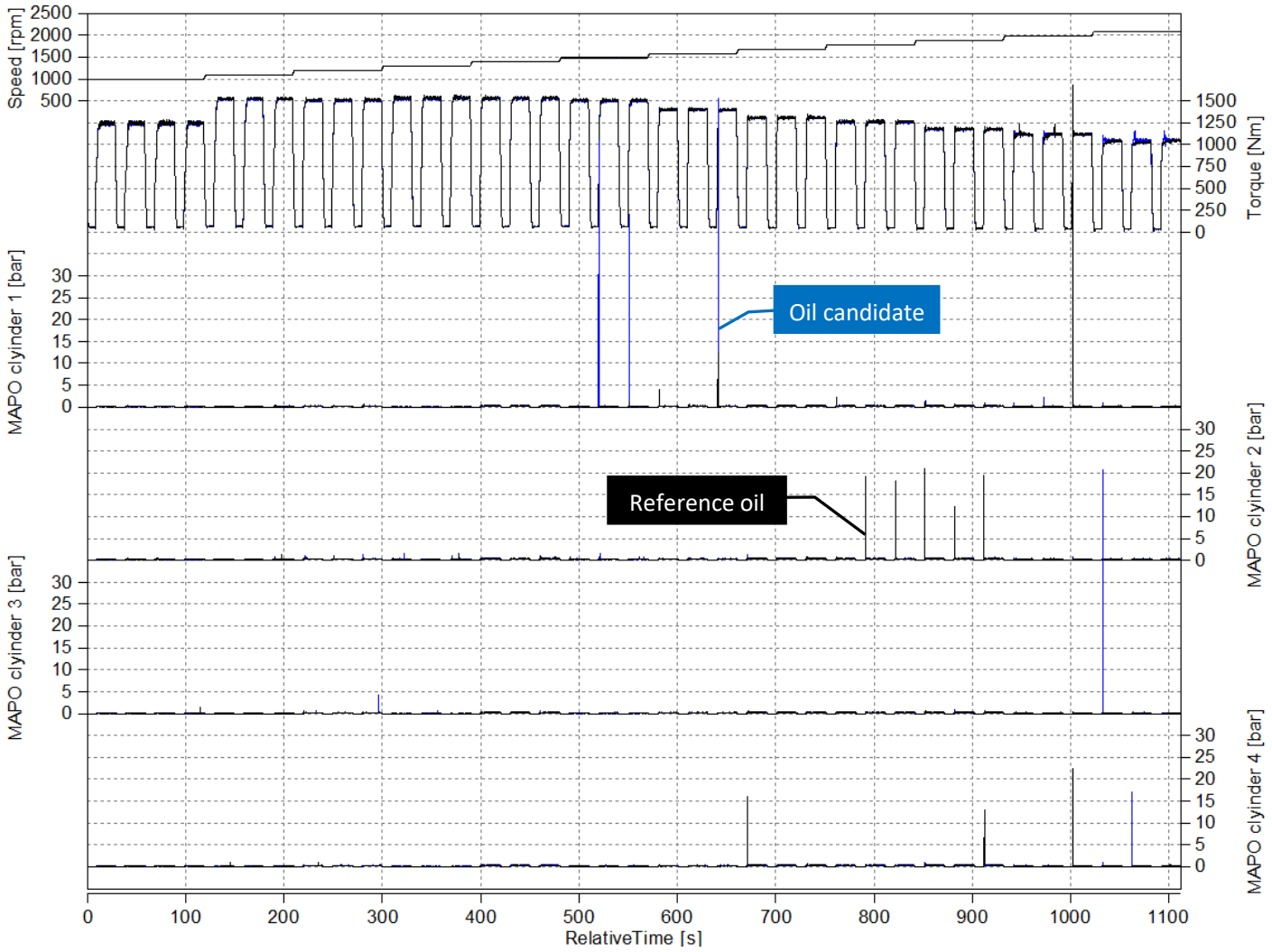


Combustion anomalies measurement methodology

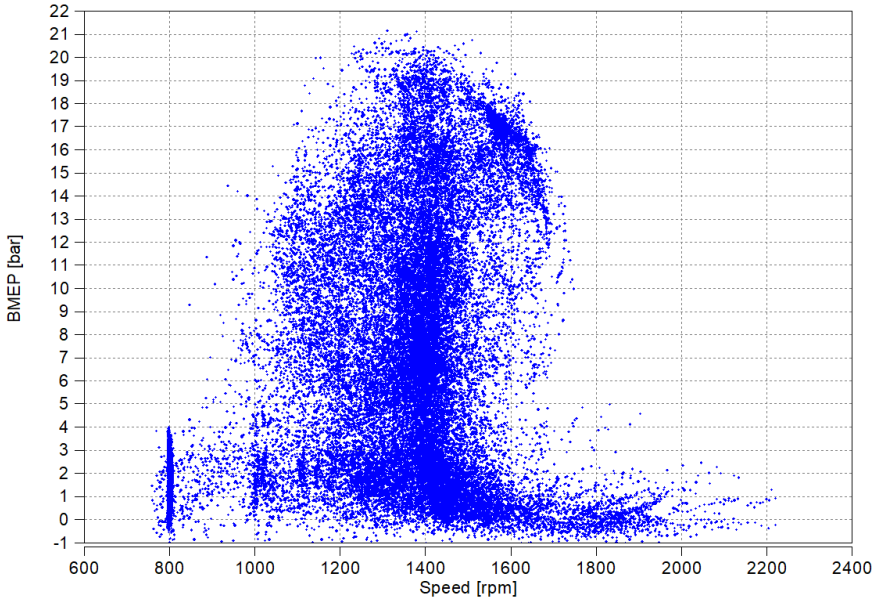
Transient measurement of combustion anomalies to favor oil transport to combustion chamber from throttled engine operation to full load. 3 load steps for each speed with increments of 100rpm.

Example of number of knock events ≥5bar recorded with cylinder pressure sensors during repeated load steps from 5% load to 100% load with constant engine speed:

Reference oil	Oil candidate
10	5



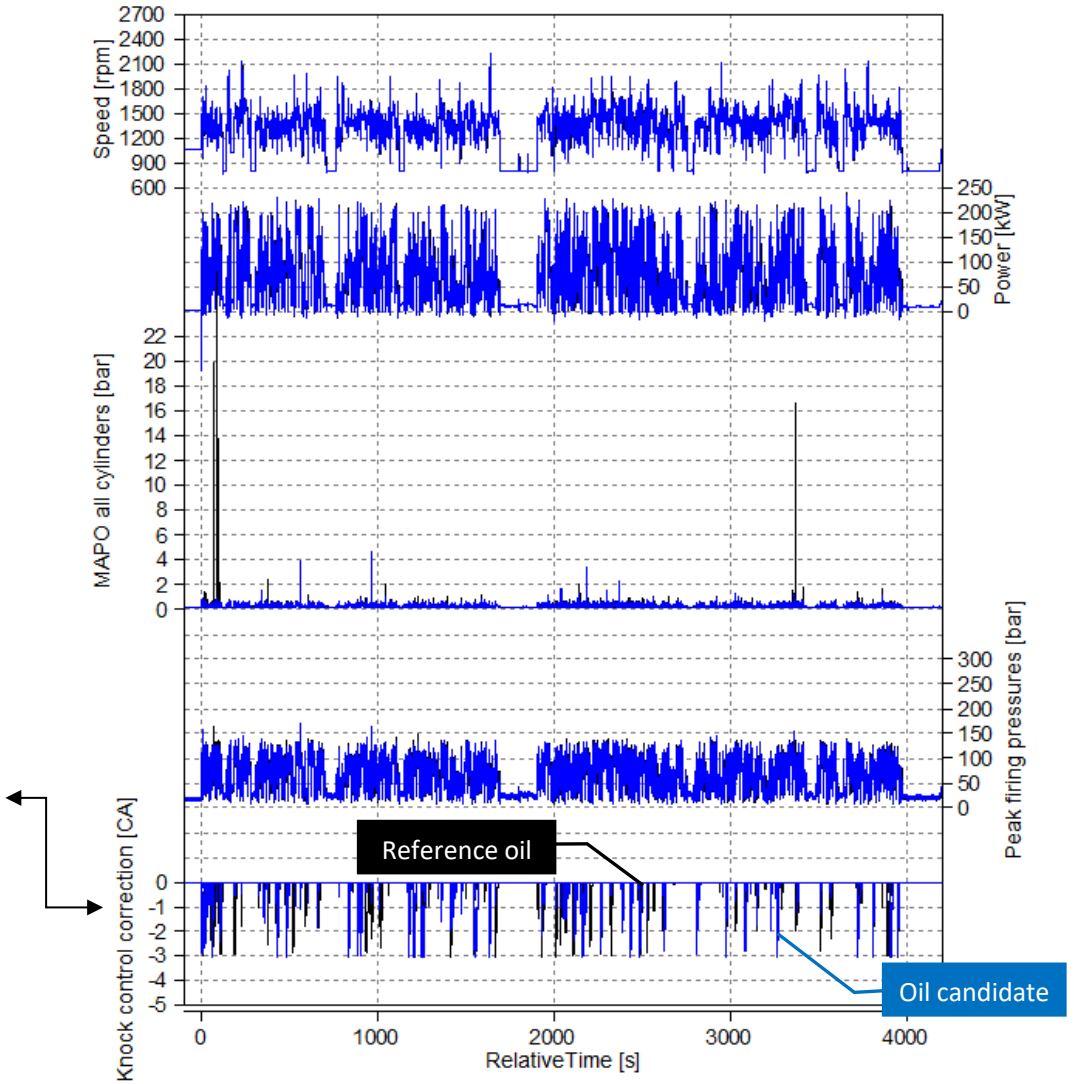
Combustion anomalies measurement methodology



Transient measurement of combustion anomalies to simulate typical wheel loader machine cycle on engine test bench.

Example of number of **knock controller correction output** recorded with cylinder knock sensors during wheel loader machine cycle:

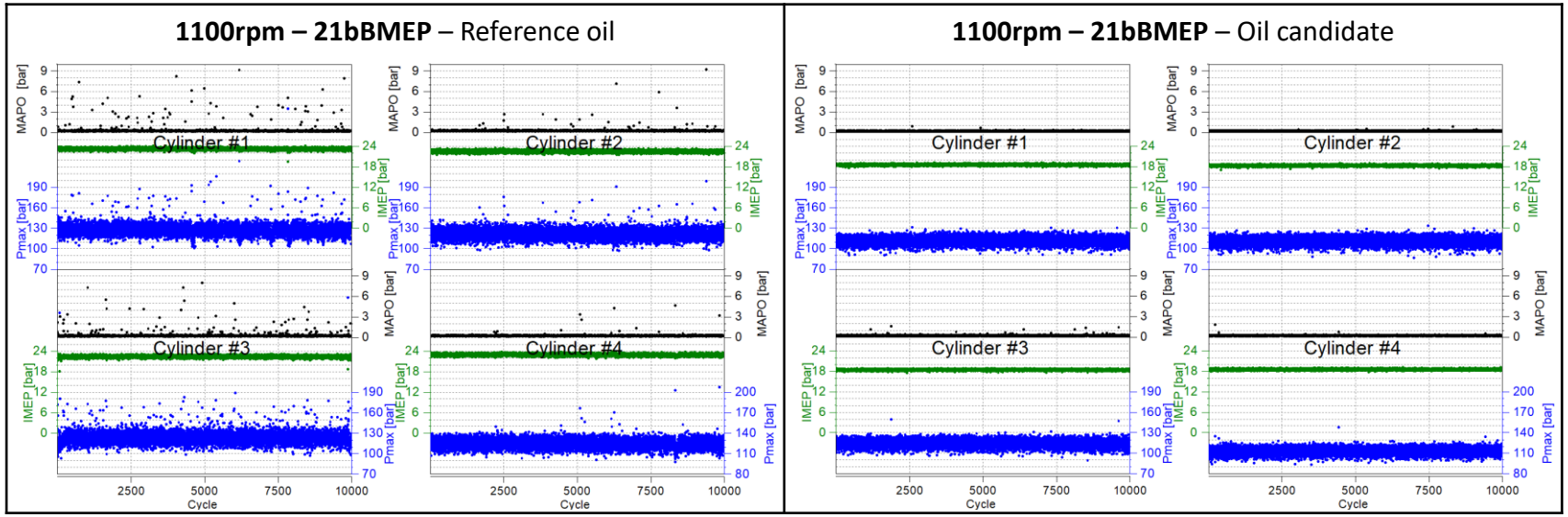
Reference oil	Oil candidate
8,9%	7,3%



Results for combustion anomalies in steady-state at low speed

Significant **reduction of combustion anomalies** (knock events and peak cylinder pressure) at **low speed** during steady-state measurement with oil candidate with the following differences:

- Different base group
- Increased **viscosity**
- Decrease of magnesium
- Increase of **molybdenum**



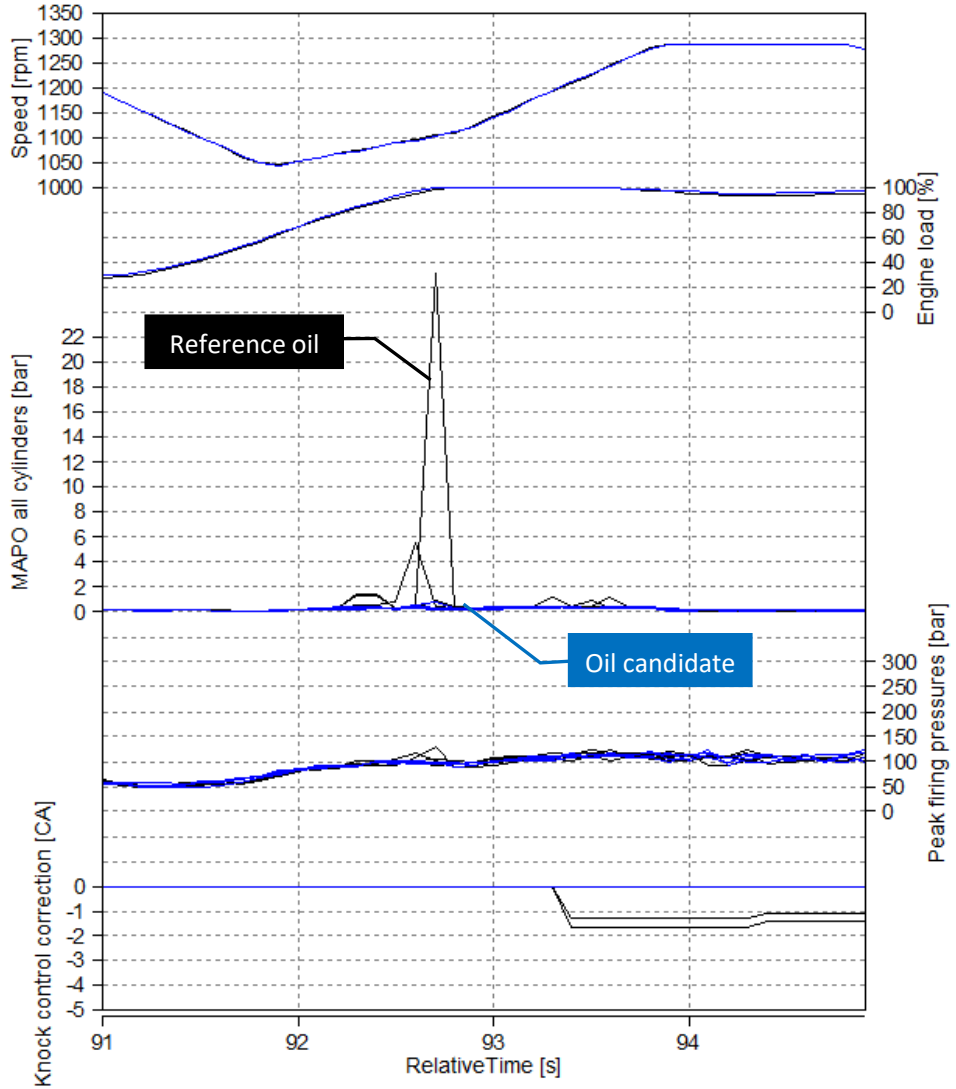
- At medium speeds the benefit of the oil candidate on combustion anomalies reduction is marginal.
- Unlike LSPI oils for gasoline passenger car ICE, the calcium content in the oil does not reduce combustion anomalies at low speed on the Liebherr H_2 ICE.

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Results for combustion anomalies in transient operation

Transient measurement of combustion anomalies to simulate typical wheel loader machine cycle on engine test bench.

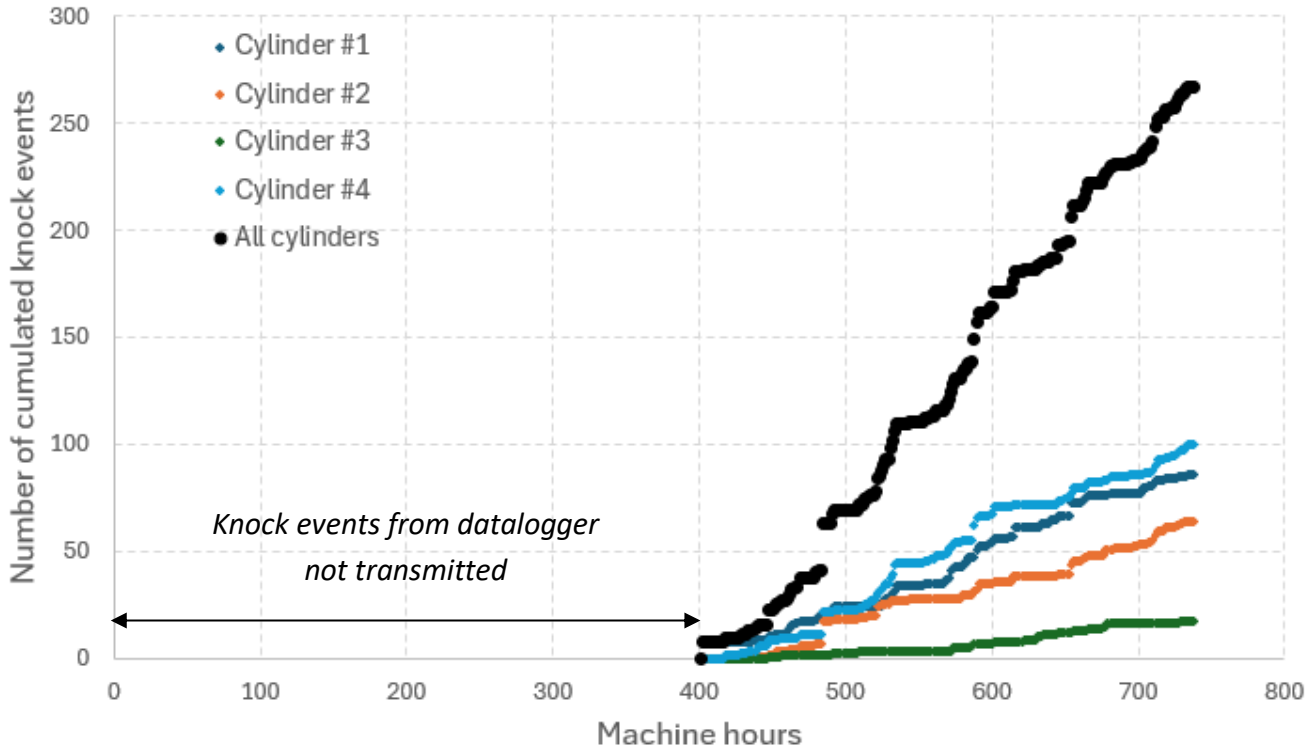
Example of number of **knock event at low speed** recorded with cylinder pressure sensors during sudden load increase at low speed during wheel loader machine cycle on engine bench with 2 different lube oils.



Knock events statistics in field tests machines

Engine knock events collected on field test machine in Austria with datalogger and Reference oil:

Knock events detected by knock sensors follow a **linear trend** indicating low sensitivity to ambient conditions, seasons, driving cycles, ageing and drivers inputs.

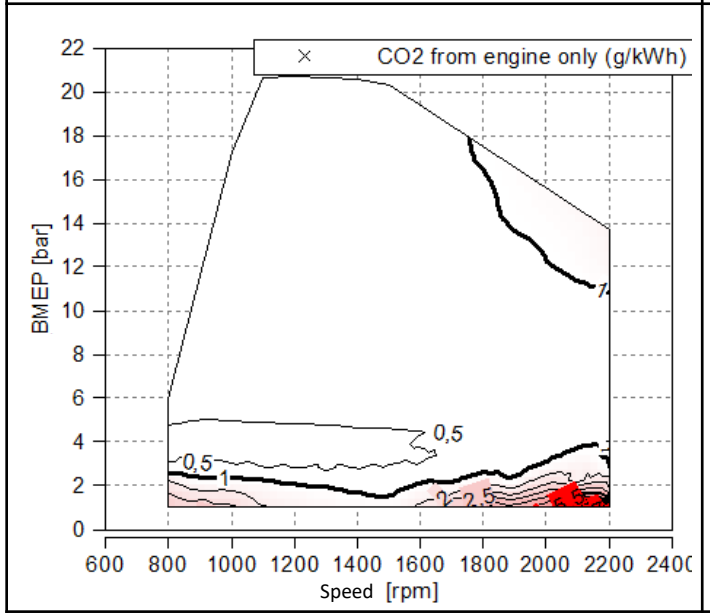


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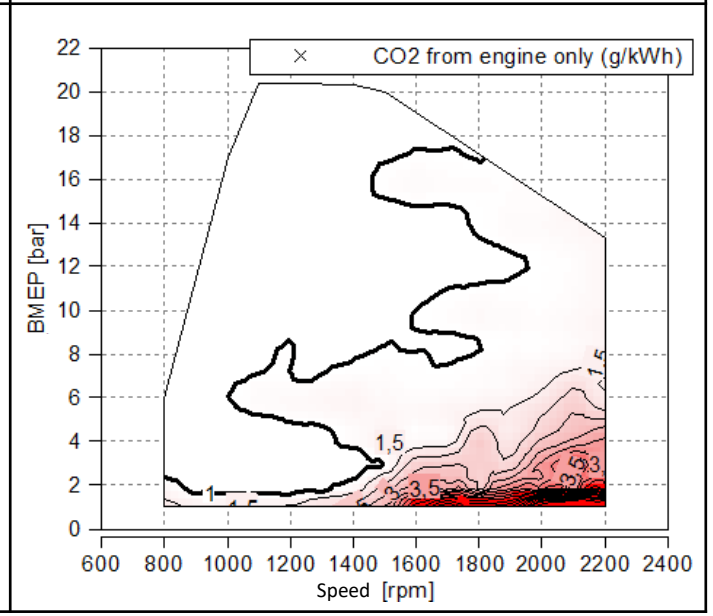
Steady-state results for carbon emissions

Engine-out specific CO_2 in steady-state measured at the exhaust: CO_2 originates from lube oil consumption and not from the fuel itself.

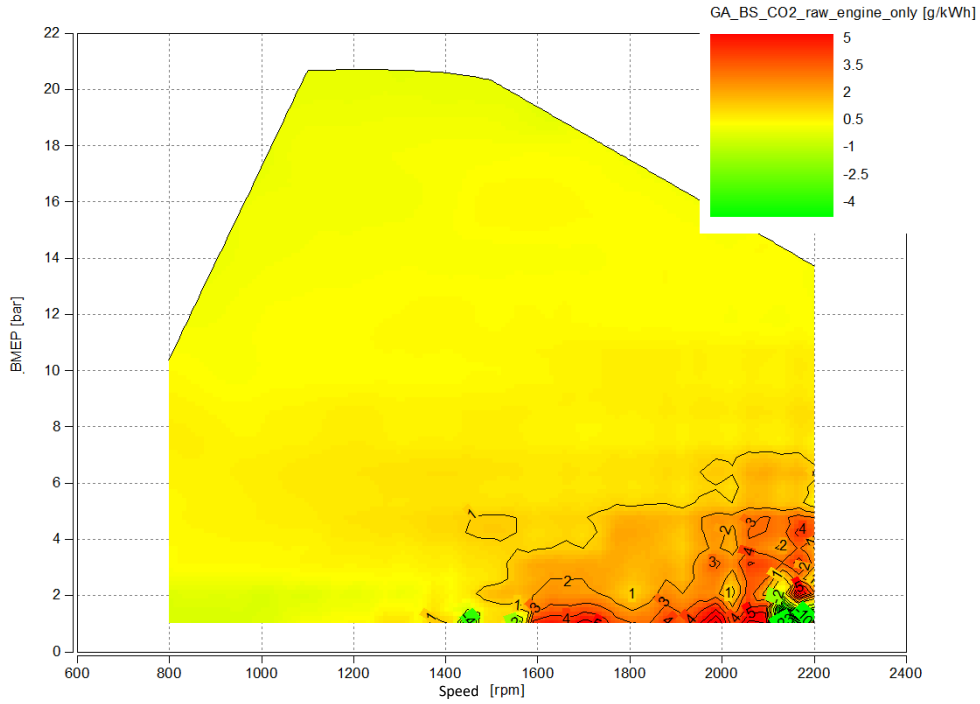
Reference oil



Oil candidate



Delta = Reference oil - Oil candidate

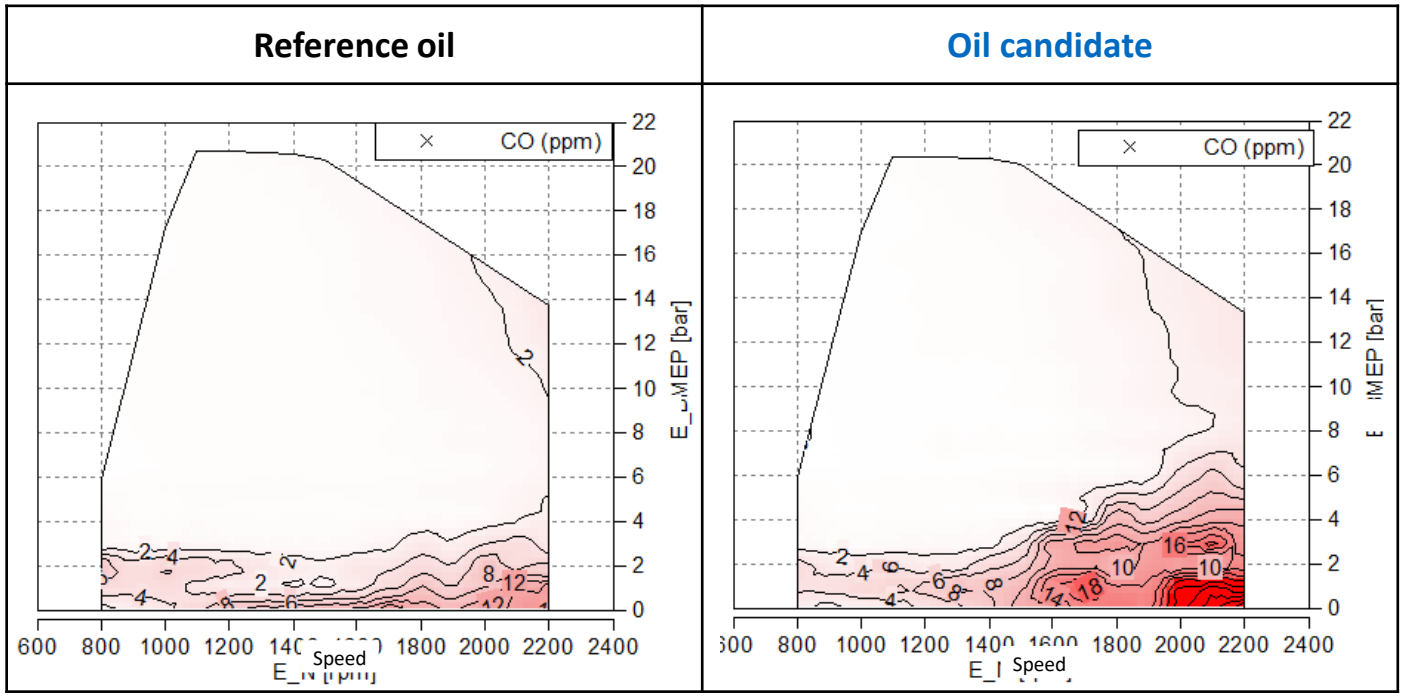


Significant **increase of specific engine-out CO_2** at high speed and low loads: impact of base group and/or viscosity.

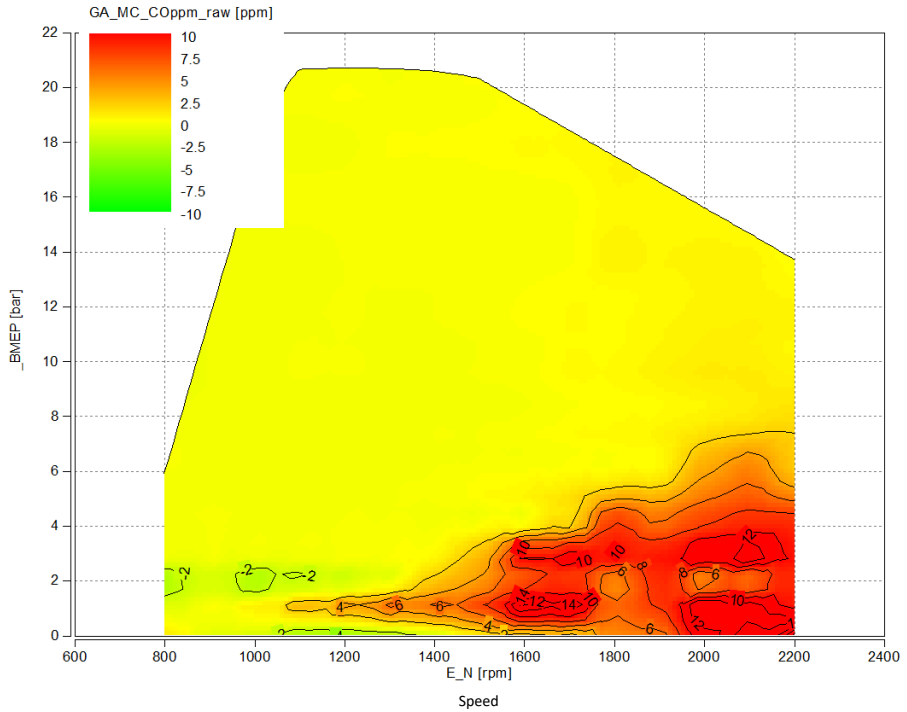
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Steady-state results for carbon emissions

Engine-out CO concentration in steady-state measured at the exhaust: CO originates from lube oil consumption and not from the fuel itself.



Delta = Reference oil - Oil candidate



Significant **increase of engine-out CO concentration** at high speed and low loads: impact of base group and/or viscosity.

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Conclusion

1. Liebherr development team created a **methodology** to quantify combustion anomalies.

2. Oil formulation optimization can help to reduce combustion anomalies such as knock in steady-state and during transient operation at **low speeds**: 1100rpm-1200rpm. Impact on medium speeds is marginal. Confirmation that the Liebherr H_2 ICE is sensitive to oil transport from liner to combustion chamber.

3. The main drivers are the lube oil **base group**, lube oil **viscosity** and **molybdenum** content to reduce combustion anomalies at low speed. However base lube oil group changes alone are insufficient to provide significant impact on knock. The calcium content in lube oil does not reduce combustion anomalies at low speed.

4. Oil formulation has an impact on **carbon emissions**.

Thank you for your attention

Contact information

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