MARC SENS (ED.)

IAV SPARK26

IAV Symposium on Pre-ignition, Auto-ignition, Reactivity, and Knock

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Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.dnb.de abrufbar.

DOI: https://doi.org/10.24053/9783381168620

© 2026 · expert verlag
– Ein Unternehmen der Narr Francke Attempto Verlag GmbH + Co. KG
Dischingerweg 5 · D-72070 Tübingen

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Internet: www.narr.de
eMail: info@narr.de

Druck: Elanders Waiblingen GmbH

ISBN 978-3-381-16861-3 (Print)
ISBN 978-3-381-16862-0 (ePDF)

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Foreword

Dear Colleagues,

Welcome to the proceedings of **IAV SPARK26**, a symposium that brings together leading experts from industry, academia, and research institutions to exchange knowledge and discuss the latest developments in ignition, combustion, reactivity, and knock phenomena.

The mobility sector is currently experiencing one of the greatest transformations in its history. While electrification and hybridization will play a central role in future transportation and energy systems, internal combustion engines continue to offer significant advantages in many applications. Their role is evolving through the integration of hybrid powertrains, advanced combustion concepts, and renewable fuels.

More than two decades after the establishment of this conference series, the topics of ignition and combustion are more relevant than ever. Emerging technologies such as prechamber ignition, together with alternative fuels including hydrogen, methanol, ammonia and others, create new opportunities for improving efficiency and reducing greenhouse gas emissions. At the same time, they introduce new challenges. Highly reactive fuels may increase the risk of pre-ignition, while fuels with lower ignitability require advanced ignition strategies and a deeper understanding of combustion processes.

Addressing these challenges is essential for the rapid deployment of sustainable energy carriers and the achievement of climate goals. Reducing greenhouse gas emissions within a short timeframe will require the use of all available technological solutions, including electrification, hybridization, and renewable fuels. As renewable energy remains a valuable and limited resource, continuously improving overall powertrain efficiency, including combustion efficiency, is of utmost importance.

This **IAV SPARK26** provides an outstanding platform for researchers, engineers, OEMs, suppliers, and technology partners from around the world to present innovations, share research results, and discuss practical solutions. The technical contributions collected in these proceedings demonstrate how advanced ignition and combustion technologies can support both existing vehicle fleets and future mobility concepts.

We would like to thank all authors, speakers, partners and sponsors for their valuable contributions. Their commitment and expertise continue to make **IAV SPARK** a globally recognized forum for scientific exchange and technological progress.

We hope that these proceedings inspire new ideas, foster collaboration, and contribute to the continued advancement of efficient, sustainable, and innovative internal combustion engines.

Berlin, 2026

Marc Sens (IAV GmbH) & The IAV SPARK26 Scientific Advisory Board

Experimental Investigations of Oil-induced Combustion Anomalies in Hydrogen Engines using Dosing and Engine-Based Methods

Peter Kappacher[1], David Kapeller[1], Paul Christoforetti,[1] Peter Günter[2], Theo Maulbetsch[3], Gottfried Lurf[4]

Abstract: Hydrogen engines represent a promising propulsion technology for future applications, particularly in the heavy-duty sector, where they offer a compelling alternative to conventional diesel engines. However, several challenges remain, one of the most critical being the susceptibility of hydrogen engines to combustion anomalies such as knock, pre-ignition, and backfire. A potential contributor to these irregular combustion phenomena has been identified in the engine oil. Oil droplets can act as hot spots within the combustion chamber, potentially triggering unintended ignition of the air–fuel mixture. This study investigates the influence of different engine oil compositions on the occurrence of combustion anomalies. In an initial step, certified test oils are evaluated by introducing a defined quantity into the intake duct of one cylinder of a 2-liter direct-injection (DI) hydrogen engine. For this purpose, a dedicated test methodology developed at TU Graz is applied. To validate this method, the selected oils are subsequently used as lubricants in a heavy-duty port fuel injection (PFI) hydrogen engine. Their impact on anomalous combustion behavior is then assessed under both steady-state and transient operating conditions. For steady-state operation, a dedicated anomaly assessment methodology developed within the Hylley project is employed. This method enables a rapid and reproducible evaluation of multiple parameters related to anomaly propensity. In transient operation, combustion anomalies are quantified in the standardized World Harmonized Transient Cycle (WHTC). The results reveal significant differences in anomalous combustion behavior among the investigated oil candidates in the oil-dosing experiments. These trends are consistently reproduced in both steady-state and transient tests on the heavy-duty hydrogen engine. Overall, a strong correlation between the different assessment methods is observed, demonstrating that the oil-dosing approach provides reliable and transferable insights into real engine operation across different engine configurations.

1 Graz University of Technology
2 Liebherr Machines Bulle SA
3 Fuchs Lubricants Germany GmbH
4 AVL List GmbH

1 Introduction

The global drive to reduce greenhouse gas emissions has intensified the search for sustainable, high-efficiency propulsion systems. Among the promising alternatives, hydrogen-fueled spark-ignited internal combustion engines (SI H_2-ICEs) have gained significant attention due to their potential for carbon-free operation while maintaining the advantages of established engine technologies. Hydrogen offers several favorable combustion characteristics, including wide flammability limits, high laminar flame speed, and excellent combustion efficiency. However, these same properties, combined with its very low ignition energy and high diffusivity, also render premixed and stratified SI hydrogen engines particularly susceptible to combustion anomalies. These combustion anomalies limit both the achievable full-load performance and the transient response of hydrogen internal combustion engines. Consequently, mitigating abnormal combustion under real-world operating conditions is essential to ensure robust, reliable, and high-performance engine operation, enabling H_2-ICEs to serve as a viable alternative to conventional diesel propulsion systems in heavy-duty applications. The following section provides an overview of anomalies that can occur in hydrogen engines. [1]

Pre-Ignition

Pre-ignition (PI) is generally defined as the ignition of the air-fuel mixture after intake valve closing (IVC) but before the spark event. Such events result in elevated cylinder pressures, which can cause engine damage. If ignition occurs before IVC, the flame can propagate into the intake system, resulting in backfire, which represents a particularly severe form of pre-ignition in port-fuel-injected (PFI) engines [2]. Additionally, the early increase in cylinder pressure caused by an occurring PI, can cause knocking within the same cycle. This results in combined pre-ignition and knock (PI-Kn), which combines the detrimental effects of both phenomena and therefore represents the combustion anomaly associated with the highest risk of engine damage [3]. The literature consistently identifies localized high-temperature ignition sources as the primary initiators of pre-ignition, including overheated exhaust valves, hot residual gases trapped in crevices, spark plug-related hot surfaces or discharge irregularities, combustion chamber deposits, and other impurities [2], [4].

More recently, the ingress of lubricant oil into the combustion chamber has emerged as an additional contributory factor to pre-ignition. Numerical kinetic investigations have demonstrated that lubricant oil chemistry can increase the reactivity of the charge and reduce ignition delay under engine-relevant conditions, particularly at the lower and intermediate temperatures encountered during the compression stroke [5]. Experimental studies support these findings by showing that the introduction of oil droplets into the intake system significantly increases the occurrence of combustion anomalies under controlled operating conditions [6]. Based on these observations, dedicated test procedures have been developed to evaluate the combustion anomaly tendency of different engine lubricants [7]. Oil can be introduced to the combustion chamber via different ways: evaporated oil mist from the liner, the piston ring package, oil from the turbocharger, valve stem seals or crank case ventilation system are among the most important [8].

Once introduced into the cylinder, oil can contribute to pre-ignition either through deposit formation or through the direct ignition of oil droplets. Deposits can act as ignition sources by creating localized hotspots within the combustion chamber. Furthermore, pressure oscillations during knocking combustion can detach deposit fragments, which may act as an additional trigger for pre-ignition events. [9]

In the case of oil droplet-induced pre-ignition, volatile oil components evaporate at elevated temperatures, forming a locally enriched oil–air mixture. If the local conditions reach the self-ignition limits of the oil, oxidation and flame propagation can occur. The released energy may subsequently ignite the surrounding hydrogen–air mixture before the intended spark event, resulting in pre-ignition. The occurrence of this mechanism depends on factors such as droplet size, oil composition, temperature, and residence time within the combustion chamber. [7]

In addition to lubricant oil effects, the exceptionally low minimum ignition energy of hydrogen makes locally rich mixture zones particularly vulnerable to spontaneous ignition when exposed to localized heat sources. Several studies have identified mixture formation as a key factor for abnormal combustion [1], [10].

Knock

Hydrogen knock is primarily associated with end-gas auto-ignition and the subsequent generation of pressure waves. Experimental and optical investigations have shown that knock intensity is strongly influenced by parameters such as compression ratio, air-fuel ratio, spark timing, and engine speed. Compared to gasoline engines, hydrogen engines exhibit distinct knock characteristics due to the specific combustion properties of hydrogen, including differences in knock onset behavior and pressure oscillation frequencies [11]. Previous investigations have demonstrated that knock in hydrogen engines can, similar to gasoline engines, be mitigated by retarding the ignition timing [3]. However, the underlying knock behavior differs significantly from conventional gasoline operation. Instead of a gradual transition from stable combustion to increasing knock intensity with advancing ignition timing, hydrogen engines can exhibit a highly stochastic knock occurrence. Under knock-prone conditions, a large number of consecutive cycles may show normal combustion, while individual cycles experience severe knock events. This abrupt transition and cycle-to-cycle variability make the application of conventional knock control strategies significantly more challenging in hydrogen operation.

Coupled Anomalies

Increasing evidence suggests that combustion anomalies should not be considered independent events but rather interactive processes. Pre-ignition and backfire increase component temperatures and create thermal hotspots that promote subsequent knock, while severe knock can generate additional hotspots that increase the probability of pre-ignition in following cycles [2]. This self-reinforcing interaction becomes particularly critical under rich operating conditions and highlights the importance of considering combustion anomalies as coupled phenomena rather than isolated events.

Improving mixture preparation, reducing thermal hotspots, and controlling ignition sources remain essential for achieving robust and efficient hydrogen engine operation [1]. In addition, previous studies have identified various operating parameters influencing

combustion anomaly behavior, including engine speed, load, air excess ratio (λ), ignition timing, intake and coolant temperatures, and intake air humidity [3], [8]. The influence of these parameters demonstrates that combustion anomaly formation is governed by a complex interaction of multiple factors rather than a single dominant cause. Although considerable progress has been made in understanding abnormal combustion mechanisms in hydrogen SI engines, several aspects of their formation and the interaction of contributing factors are not yet fully understood.

This paper addresses oil induced combustion anomalies and defines a framework to assess different engine oil compositions regarding their appearance. A dedicated test procedure using a special oil dosing method into the intake manifold has been developed and published in [7]. However, this method does not address the investigation of anomaly formation in instances where oil is utilised as the lubricant within the engine. The present paper aims to verify the results obtained with the dosing method. In order to do so, dedicated measurements are obtained on a different engine using dedicated test-oils as the engine lubricant.

2 Methods

2.1 Dosing

To investigate the influence of different engine oils on the occurrence of combustion anomalies, a dedicated test procedure is employed. This test procedure, together with the overall methodology, was developed at the Institute Thermodynamics and Sustainable Propulsion Systems at Graz University of Technology [7].

2.1.1 Engine

The oil dosing procedure is conducted on a Mercedes-Benz M274 four-cylinder inline spark-ignition engine with a displacement of 2.0 L. The light-duty (LD) engine features a compression ratio of 9.8 and direct fuel injection with rail pressures of up to 175 bar. The production Bosch HDEV4 injectors are centrally positioned in the combustion chamber, while prototype spark plugs are installed in an offset position relative to the injectors. In-cylinder charge motion is characterized by a tumble flow.

The intake air is initially compressed by a diesel turbocharger equipped with variable turbine geometry (VTG) and subsequently conditioned to the desired temperature using the original charge air cooler. The exhaust aftertreatment system is retained in its standard configuration and comprises a three-way catalytic converter and a rear silencer. Engine operation is controlled by a fully programmable ECU originally designed for motorsport applications.

A schematic representation of the test bench setup is shown in Fig. 1. With the configuration described above, the engine achieves a maximum power output of 120 kW at 4000 rpm and a brake mean effective pressure (BMEP) of 22 bar at 2000 rpm [12].

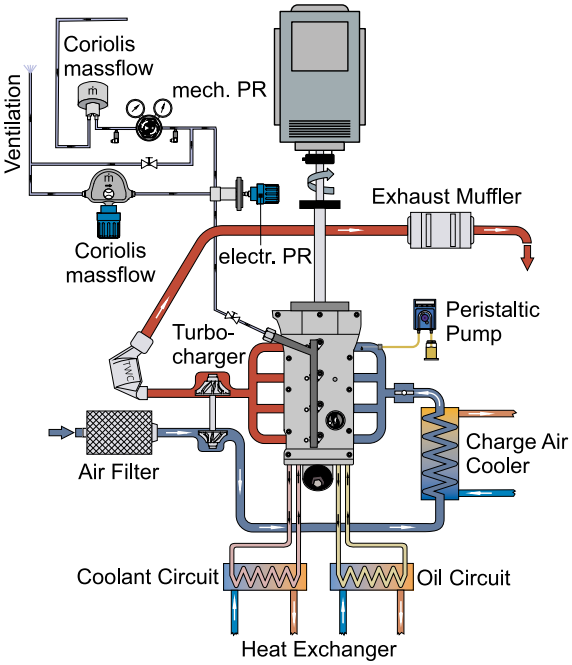


Fig. 1: Schematics of the M274 Engine

2.1.2 Dosing Setup

Oil dosing is performed through a dosing lance with an inner diameter of 2 mm, which is installed in the intake port of the fourth cylinder. To ensure controlled droplet detachment, the oil is introduced normal to the flow direction in the intake port, with the dosing lance positioned centrally at the level of the right intake valve. The desired oil flow rate is supplied by a peristaltic pump.

The dosed oil quantity is determined redundantly by means of an online precision balance and by calculating the oil mass using the carbon balance method during post-processing. The applied oil mass flow rate is selected to represent the oil consumption level of a worn engine. The calculation of the dosed oil quantity based on the carbon balance is described in detail in [7]. It should also be noted that the engine's inherent oil consumption is mathematically eliminated from the carbon balance, ensuring that only the externally dosed oil mass is considered.

The online data acquisition from the precision balance enables closed-loop control of the supplied oil mass flow rate using a PID controller with feedforward control. This approach minimizes the influence of factors affecting the dosed oil quantity, primarily differences in oil viscosity, as well as manufacturing tolerances and wear of the pump tubing. A schematic representation of the oil dosing system is shown in Fig. 2.

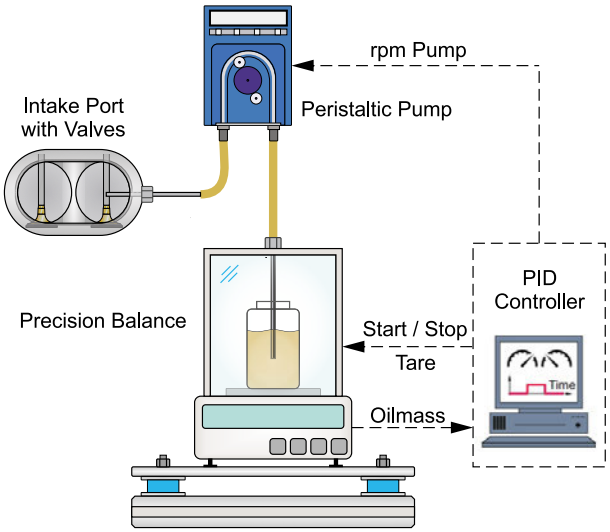


Fig. 2: Schematics of the Oil Dosing Setup

2.1.3 Dosing Test-Run

The steady-state test procedure consists of three phases. Initially, a 10 min preconditioning and stabilization phase is performed. Subsequently, the oil under investigation is dosed for the same duration, followed by a 5 min post-conditioning phase. To ensure consistent operating conditions for each test, a BMEP controller is activated during the steady-state test procedure. The main engine operating parameters for the load point used during the dosing tests are summarized in Tab. 1.

Throughout the entire test procedure, data from each individual combustion cycle as well as all relevant low-frequency measurement signals are recorded continuously. Combustion anomalies occurring during the oil dosing phase and thus attributable to the dosed oil are detected and evaluated during post-processing, using the methodology described in section 2.3. Fig. 3 shows the normalized oil mass flow rate calculated based on the carbon balance. As previously mentioned, the engines inherent oil consumption is eliminated from the calculation.

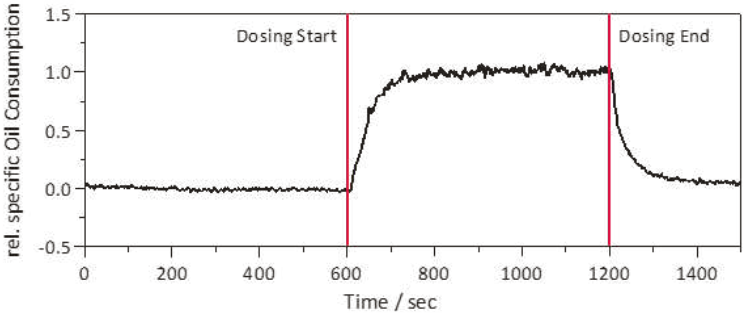


Fig. 3: Relative specific Oil Consumption of an Oil Dosing Test

Parameter	Unit	Value
BMEP	bar	14
Speed	min^{-1}	1550
Lambda	-	1.7
$MFB_{50\%}$	°CA	12

Tab. 1: Engine Operating Parameters for the Oil Dosing Procedure

2.2 Engine based assessment methods

2.2.1 Engine

The results obtained with the dosing method should be verified using the test oil as the engine lubricant in a completely different engine setup. For this, the samples are filled into a Liebherr H964 Heavy-Duty H_2-engine, which is derived from a diesel platform. The engine features a port fuel injection (PFI) system with a maximum hydrogen injection pressure of 15 bar, regulated by a dual-stage pressure regulation system. Spark ignition is provided by centrally positioned spark plugs and a variable-energy capacitive ignition system. Compared to the diesel baseline, the compression ratio was reduced to 11, and the charge air system was redesigned to enable lean-burn operation. A dual-stage fixed-geometry turbocharging system with intercooling after each compressor stage and a high-pressure wastegate provides the required boost pressure, while the injected fuel quantity is controlled via load- and speed-dependent lambda control. A fixed exhaust flap simulates the backpressure of a future exhaust aftertreatment system (250 mbar at rated power). Engine operation is managed by a prototype Schaeffler Protronic ECU, allowing flexible calibration for experimental studies. The engine delivers a rated power of 230 kW and a maximum brake mean effective pressure (BMEP) of 17.8 bar at 1500 rpm, with performance currently limited by combustion anomalies. Fig. 4 shows schematics of the engine.

The investigated engine differs fundamentally from the M274 engine used in the oil-dosing experiments. Key differences include engine size (HD vs LD-engine), mixture formation strategy (port fuel injection vs. direct injection), in-cylinder charge motion (swirl vs. tumble), and the boosting system (dual-stage fixed-geometry turbocharging vs. single-stage variable turbine geometry turbocharging). These differences should demonstrate the transferability of the oil-dosing results to a broader range of engine concepts and real-world heavy-duty hydrogen engine applications.

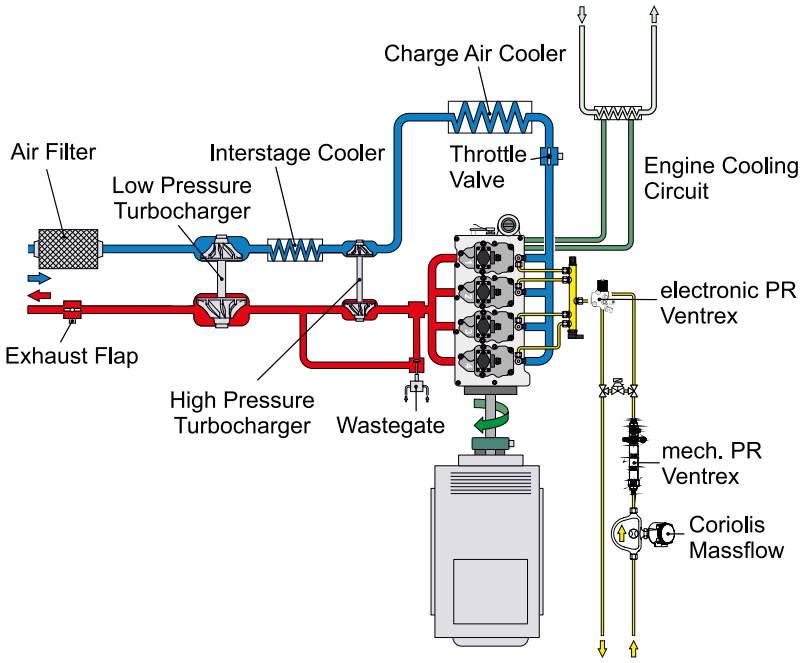


Fig. 4: Schematics of the H964 engine

2.2.2 Stationary assessment

To validate the results obtained from the oil-dosing method, the combustion anomaly tendency of the investigated test oils is experimentally assessed on the H964 engine under both stationary and transient operating conditions. The engine is subjected to dedicated test procedures during which combustion anomalies are monitored and quantified. The stationary and transient test procedures are described in the following sections.

Stationary assessment of the combustion anomaly tendency is conducted using a standardized test procedure developed at the Institute of Thermodynamics and Sustainable Propulsion Systems [3]. The method enables a rapid and reproducible quantification of combustion anomalies while minimizing the risk of engine damage. Although the test is performed under conditions that differ from the standard engine calibration, it has previously demonstrated good reproducibility and transferability of the obtained results [1], [3], [10].

The stationary test procedure consists of eight phases (Fig. 5). Two stabilization phases are carried out at a low-load operating point (1700 rpm, 4 bar BMEP), followed by two anomaly assessment phases at 1700 rpm and 8.4 bar BMEP. The engine is transitioned between both operating points by four quasi-stationary ramps, each lasting 20 s. Although the assessment load point is well below the engine's full-load capability, combustion anomalies are intentionally promoted by reducing the air-fuel ratio and adapting the ignition timing. This operating strategy provides sufficient margin to the maximum cylinder pressure in case of an anomaly and therefore mitigates potential engine damage. Fig. 5 illustrates the corresponding profiles of engine load, combustion timing, and air excess ratio during the test procedure. Throughout the entire test, in-cylinder pressure is

recorded cycle-by-cycle for all four cylinders. The method described in Section 2.3 is used to detect anomalies occurring during the test, using adapted threshold values for $MFB_{05\,\%}$, KP_{Int} and p_{max}.

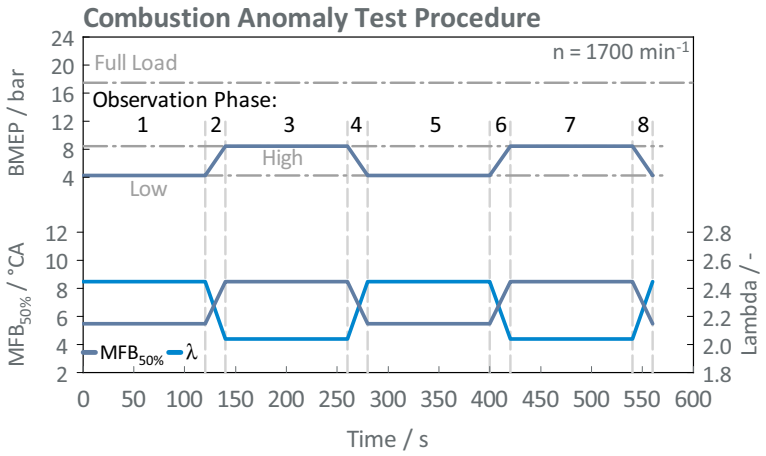


Fig. 5: Stationary combustion anomaly test procedure [3]

Representative examples of the different anomaly types are shown in Fig. 6. The outcome of the procedure is the anomaly count of each type during the test.

This metric serves as the experimental indicator for the combustion anomaly tendency in a specific engine configuration. It should be noted that, although the procedure reliably quantifies the occurrence of combustion anomalies, it does not allow conclusions regarding their underlying physical root causes [3].

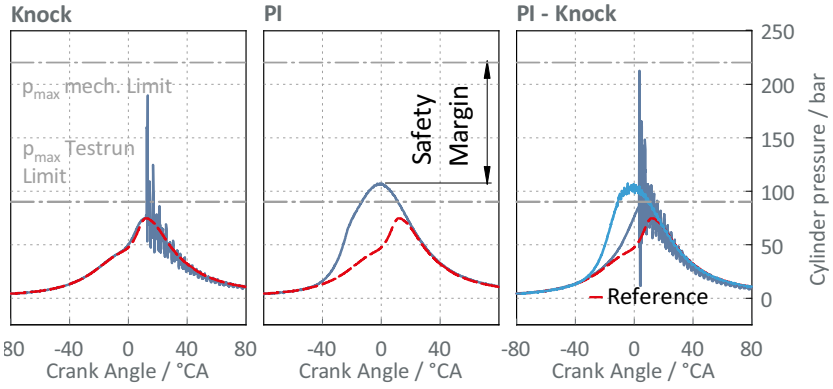


Fig. 6: Examples for different anomaly types on the H964 engine [1]

2.2.3 Transient assessment

Transient assessment is done by performing a World Harmonized Transient Cycle (WHTC). Fig. 7 presents the corresponding speed and load curves for the H964 engine. For combustion anomaly assessment, a dedicated evaluation methodology was developed within the Hylley project. During transient test cycles, slow-measuring engine data is

recorded by the test bench at a sampling rate of 10 Hz, while high-resolution in-cylinder pressure data are acquired using an indicating system with crank-angle based resolution. The system continuously monitors combustion based on the same anomaly criteria applied in the stationary assessment. Whenever one or more threshold values are exceeded, the system stores the complete high-speed pressure data of the triggering cycle together with the preceding and subsequent 20 combustion cycles for all cylinders.

After completion of the test cycle, all recorded combustion cycles are evaluated in a post-processing routine using the established anomaly classification criteria (section 2.3). Each anomalous cycle is categorized as knock (Kn), pre-ignition (PI), or combined pre-ignition and knock (PI-Kn). In addition, the evaluation determines whether the peak firing pressure exceeds the safety limit of 220 bar. The resulting metrics comprise the total number of combustion anomalies, their distribution among the different anomaly types, and the occurrence of pressure limit exceedances throughout the transient test cycle. [1]

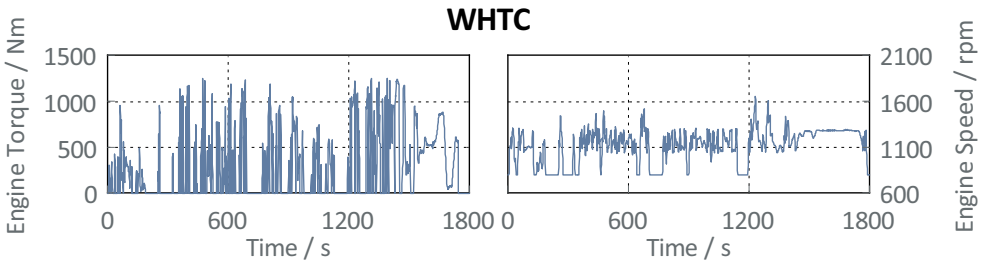


Fig. 7: Denormalized WHTC for the H964 Engine [13]

2.3 Anomaly Detection

The recorded in-cylinder pressure traces of each test are analyzed in a post-processing routine to identify combustion anomalies. The evaluation is based on threshold values for the maximum cylinder pressure (pmax), the crank angle corresponding to 5 % mass fraction burned ($MFB_{05\,\%}$), and the knock intensity (KP_{Int}). Based on the exceeded threshold values, each combustion cycle is classified as knock (Kn), pre-ignition (PI), or combined pre-ignition and knock (PI-Kn), as illustrated in Fig. 8.

A cycle is considered anomalous if the maximum cylinder pressure and at least one of the additional criteria is exceeded. Exceeding the $MFB_{05\,\%}$ threshold indicates pre-ignition, while exceeding the KP_{Int} threshold indicates knock. Simultaneous violation of all criteria is classified as a combined PI-Kn event. The threshold values are selected such that an exceedance of the maximum cylinder pressure limit (p_{max}) is always accompanied by a violation of at least one of the additional criteria. However, cycles exceeding the p_{max} limit without violating the $MFB_{05\,\%}$ threshold are only classified as knock events if the corresponding knock intensity (KP_{Int}) also exceeds its defined threshold. The evaluation is performed individually for every cylinder and every recorded combustion cycle. For the oil dosing method, the focus is primarily on the combustion anomalies occurring in cylinder 4, as the oil under investigation is dosed exclusively into this cylinder.

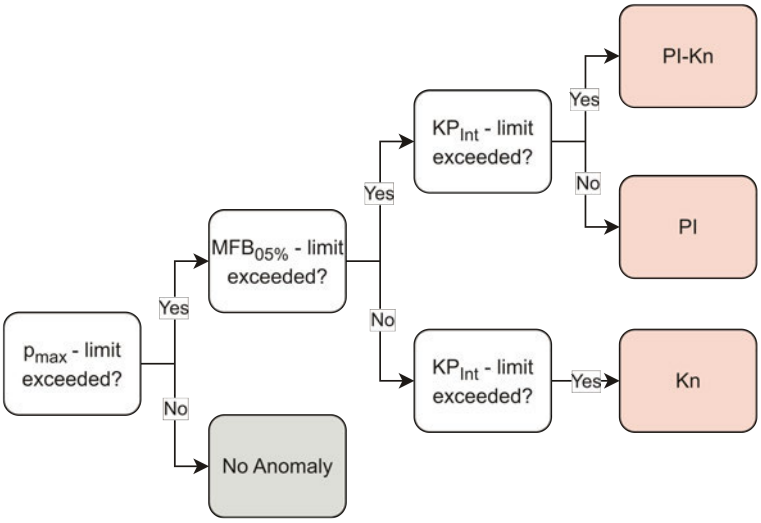


Fig. 8: Anomaly assessment

2.4 Test Oils

Four different lubricant formulations are investigated in this study. The reference oil is the standard engine oil specified for the hydrogen version of the engine. In addition, two specially blended experimental oil formulations, whose compositions were derived based on findings from previous oil-dosing investigations, are evaluated. One formulation was designed to exhibit a low combustion anomaly tendency, while the other was formulated to promote an unusually high anomaly tendency. For comparison, the standard engine oil used in the diesel variant of the engine is also included in the investigations. In order to mitigate different oil consumptions during the stationary and transient tests, all of the tested oil have similar viscosity classes. Fig. 9 shows that the oil consumtions during transient testing in the WHTC varies less than 6 % across the different test oils. Tab. 2 shows key parameters of the different oil compositions.

	Unit	Base	Low reference	High reference	Standard diesel
Viscosity class		SAE 30	SAE 30	SAE 30	5W-30
Kin. viscosity 40 °C	mm^2/s	72,33	120,7	77,5	73
Kin. viscosity 100 °C	mm^2/s	12,14	12,23	12	12
Relative Ca/Mg Content	Ca/Mg	50/50	100/0	100/0	No data
Sulfate Ash	%	0,9	0,7	0,7	0,95

Tab. 2: Key paramters of the test oils

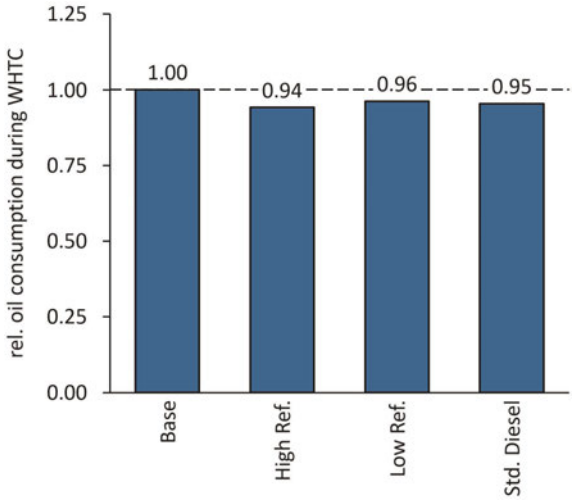


Fig. 9: Relative oil consumptions of different engine oils during the WHTC

3 Results

This chapter presents and discusses the results obtained using the experimental methods described in the previous sections. As outlined earlier, the investigation begins with the oil-dosing experiments conducted on the M274 LD-engine. The corresponding results are presented in Fig. 10.

A clear difference in combustion anomaly tendency can be observed between the investigated oil samples. As expected, the High Reference oil, which was specifically formulated to promote combustion anomalies, exhibits the highest overall anomaly count. Besides a pronounced increase in pre-ignition events, this oil also shows a significantly higher knock tendency than all other lubricant formulations.

In contrast, the remaining three oils exhibit comparatively low and similar anomaly rates. Among these, the Low Reference sample produces the lowest overall anomaly count, confirming the intended effect of its formulation. The Base- and the Diesel Reference oil show a slightly increased pre-ignition tendency compared to the Low Reference oil. Overall, these three lubricant formulations demonstrate a low susceptibility to combustion anomalies under the investigated operating conditions.

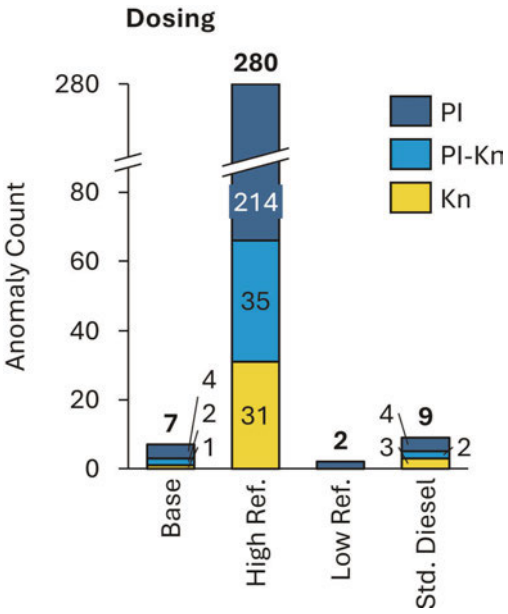


Fig. 10: Dosing results for different test oils

Dosing investigations are followed by stationary and transient tests on the H964 engine where the respective test sample is used as the engine oil. Prior to each measurement, the engine is thoroughly flushed before being filled with the respective test oil to minimize cross-contamination between tests.

The total anomaly counts in the test runs is portrayed in Fig. 11. The ranking of the investigated lubricant formulations is consistent across all three test procedures. The High Reference oil exhibits the highest combustion anomaly tendency in every assessment method, followed by the standard Diesel oil and the Hydrogen Base oil. The Low Reference oil consistently shows the lowest tendency to induce combustion anomalies. This consistent ranking demonstrates good agreement between the different evaluation methods and supports the transferability of the oil-dosing results to both stationary and transient engine operation. Additionally, the findings indicate a high degree of transferability between fundamentally distinct engine types.

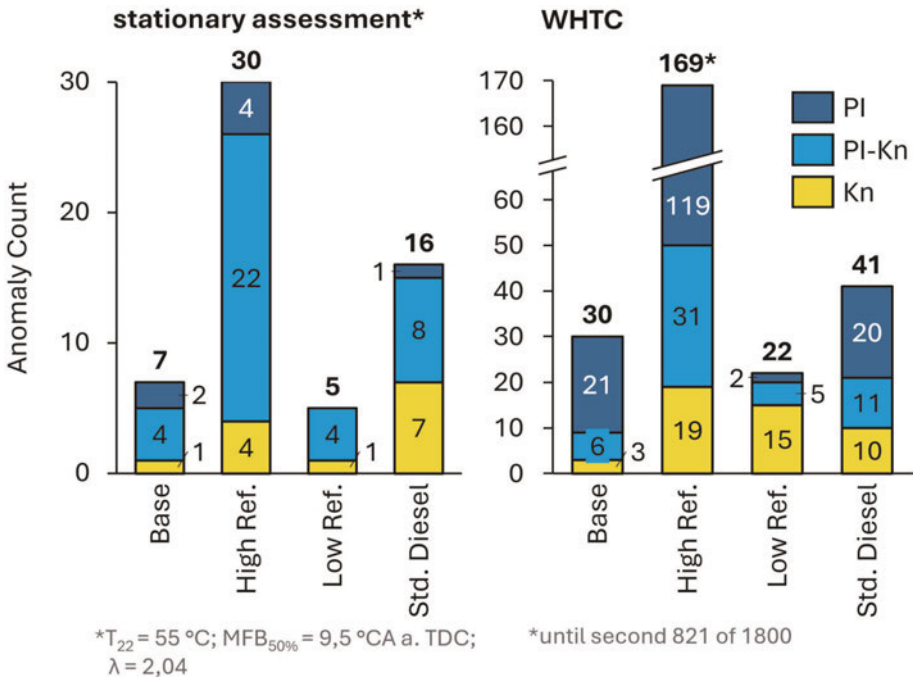


Fig. 11: Anomaly counts from stationary and transient assessment

3.1 Discussion

Although all three assessment methods yielded the same ranking of the investigated oil formulations in terms of their tendency to trigger irregular combustion, differences in the relative anomaly counts were observed. In the oil-dosing and in the transient experiments, the separation between the High Reference oil and the remaining formulations is considerably more pronounced than during the stationary engine tests. The observed differences can primarily be explained by the varying specific oil consumption associated with the individual test methods, as illustrated in Fig. 12. The specific oil consumption for each test method is determined using a carbon balance based on the measured exhaust gas composition. First, the absolute mass of lubricant entering the combustion chamber is calculated from the carbon-containing emissions (CO_2, CO, HC). This value is then normalized by the corresponding engine energy output during the test to obtain the specific oil consumption. Finally, the specific oil consumptions are normalized to the value obtained from the oil-dosing method, which serves as the reference.

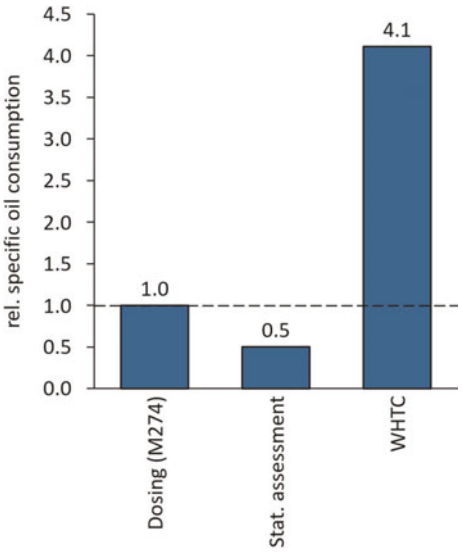


Fig. 12: relative specific oil consumption in the different test methods

In the oil-dosing method, the dosed amount is intentionally chosen to simulate the elevated oil consumption of a worn engine. Consequently, the amount of oil entering the combustion chamber is significantly higher than the actual oil consumption of the H964 engine under stationary operating conditions.

Another factor influencing the differing combustion anomaly tendency observed during the stationary assessment is the deliberately modified engine calibration. The engine is operated with a reduced excess air ratio and modified ignition timing to intentionally promote combustion anomalies. Under these conditions, lubricant-induced effects represent only one of several contributing factors to abnormal combustion, although the results clearly demonstrate that lubricant composition still has a significant influence on the combustion anomaly tendency.

During transient operation, the effective oil consumption is significantly higher than under stationary conditions. A closer examination of the data suggests that frequent load changes and extended idle phases during the WHTC are responsible for most of the increase in oil consumption. During idle operation, the intake manifold pressure after the throttle valve becomes negative, promoting lubricant ingress into the combustion chamber through the piston rings or valve stem seals, which are not designed for prolonged operation under these conditions on the given engine. An examplatory load step during the WHTC is portrayed in Fig. 13. During such transient operating phases, the instantaneous normalized oil consumption can substantially exceed the reference value of the oil-dosing method. Consequently, the influence of engine oil on combustion anomaly occurrence becomes more pronounced during the WHTC.

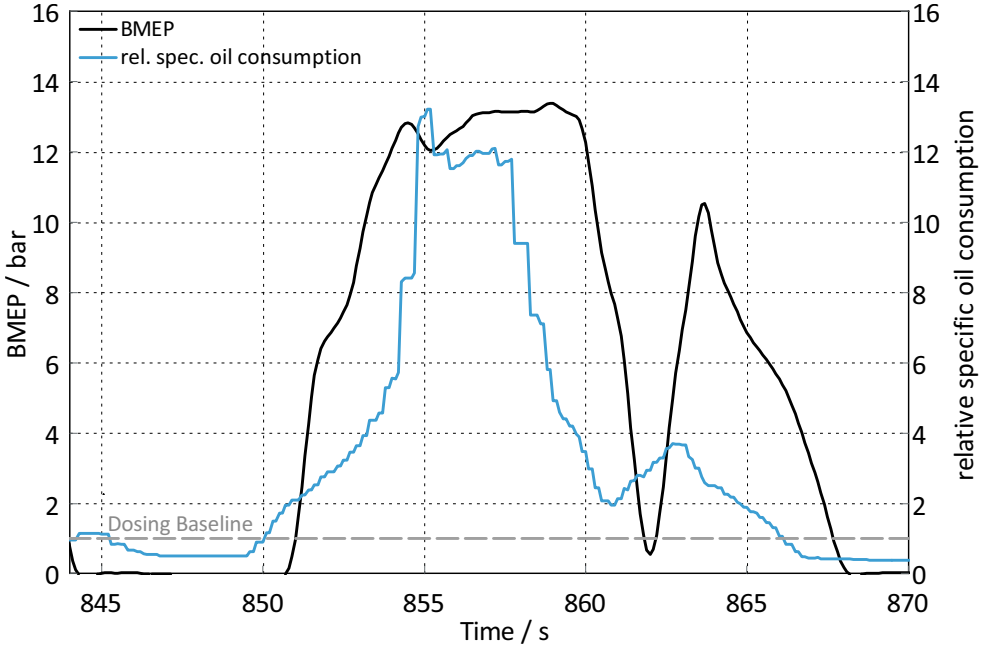


Fig. 13: Oil consumption during an examplatory load step following an idle phase within the WHTC

As a result, during the transient investigations with the High Reference oil, the combustion anomaly frequency and severity were sufficiently high that the WHTC could not be completed without exceeding the predefined safety limits. Consequently, the test was aborted after 821 s of the scheduled 1800 s test duration. However, by that point the recorded anomaly count had already exceeded that of all other lubricant formulations by a significant margin.

Small differences in the distribution of combustion anomaly types were also observed between the applied test methods. While the relative distribution of anomaly types obtained from the oil-dosing experiments agrees well with the transient investigations, the stationary assessment exhibits a higher proportion of combined pre-ignition and knock (PI-Kn) events. This behavior is attributed to the selected operating point and reduced air excess ratio increase the likelihood that pre-ignition events develop into subsequent knock. Nevertheless, the consistent ranking of the investigated lubricant formulations and the similar anomaly characteristics across the different test procedures suggest that the same lubricant-induced mechanism governs combustion anomaly initiation in all three methods.

4 Conclusion

This study demonstrates the significant influence of lubricant oil entering the combustion chamber on combustion anomaly formation in hydrogen engines, particularly with respect to pre-ignition. The investigated lubricant formulations exhibit substantial differences in their tendency to induce combustion anomalies, indicating that lubricant

composition represents an effective parameter for improving combustion robustness and extending the stable operating range of hydrogen engines.

The experimental results further demonstrate the transferability of the oil-dosing methodology. Despite considerable differences in engine architecture, mixture formation, charge motion, boosting system, and operating conditions, the ranking of the investigated lubricant formulations remained consistent between the oil-dosing experiments on the light-duty engine and the stationary and transient investigations on the heavy-duty hydrogen engine. This strong agreement confirms that the oil-dosing approach reliably captures the influence of lubricant composition on combustion anomaly tendency. The results further indicate that the underlying lubricant-related mechanism leading to combustion anomalies is comparable across different engine concepts and operating conditions.

In addition to lubricant formulation, the amount of lubricant entering the combustion chamber was identified as a key factor influencing combustion anomaly occurrence. The investigations revealed substantial differences in specific oil consumption between the applied test methods, with transient operation exhibiting markedly increased lubricant ingress during load changes and idle phases. These findings underline the importance of minimizing lubricant transport into the combustion chamber throughout the entire engine operating range and of using thoroughly tested engine oils suitable for hydrogen operation.

Owing to its good correlation with engine-based validation tests, the oil-dosing methodology provides a fast, reproducible, and engine-independent approach for evaluating the combustion anomaly tendency of lubricant formulations. By enabling rapid screening of base oils, additive packages, and lubricant concepts without repeated oil changes or extensive engine testing, the method represents a valuable development tool for future hydrogen engine lubricants and supports the early identification of formulations with a low combustion anomaly tendency.

5 Statements and Declarations

All measurements and investigations presented in this paper were conducted as part of the research project Hylley. It investigates hydrogen engines as a climate neutral and sustainable propulsion for On- and Off-Road machinery. Hylley is an international consortial research project involving partners from industry and science. The scientific partners are:

- Graz Universitiy of Technology, Institute of Thermodynamics and Sustainable Propulsion Systems (ITnA), Consortium Leader
- Montanuniversität Leoben, Department of Materials Scrience (MUL)
- HyCentA Research GmbH (HyCentA)

The industry partners are:

- AVL List GmbH
- Liebherr (with locations in Telfs, Deggendorf and Bulle)
- Hörbiger Wien GmbH

- Umicore AG
- Ventrex Automotive GmbH

Hylley is a COMET Project. The COMET Programme is financed by the federal government of Austria, the federal states Styria and Tyrol, the participating companies and research organisations. The responsible owners are the Federal Ministry of Innovation, Mobility and Infrastructure (BMIMI) as well as the Federal Ministry of Economy, Energy and Tourism (BMWET). COMET is managed by The Austrian Research Promotion Agency (FFG).



Fig. 14: Funding of Hylley

6 References

[1] Christoforetti P., Kappacher P., Plöckinger S. et. al., "Experimental and simulation-based investigation of combustion anomalies in H2 combustion engines and their effects on transient engine operation," in *47th International Vienna Motor Symposium*, Vienna, 2026.

[2] Lu Y., Que J., Liu M. et.al., Study on backfire characteristics of port fuel injection single-cylinder hydrogen internal combustion engine, Applied Energy,Volume 364, https://doi.org/10.1016/j.apenergy.2024.123110, 2024.

[3] Kappacher P., Kapeller D., Christoforetti P. et. al., Experimental Quantification and Assessment of Combustion Anomalies under defined operating conditions of a Heavy-Duty Hydrogen Engine, Automot. Engine Technol. 10, 14; https://doi.org/10.1007/s41104-025-00161-x, 2025.

[4] Dhyani V., Subramanian K. A., Development of online control system for, International Journal of Hydrogen Energy, Volume 46, Issue 27, Pages 14757-14763, https://doi.org/10.1016/j.ijhydene.2020.08.148, 2021.

[5] Distaso E., Cal`o G., Amirante R. et.al., Linking lubricant oil contamination to pre-ignition events in hydrogen, Fuel, Volume 379, https://doi.org/10.1016/j.fuel.2024.133041, 2025.

[6] Rossegger, B., Grabner, P., Gschiel, K. et.al., Towards Robust Hydrogen Combustion: Precise Lube Oil Consumption Measurement as an Enabler for Tackling Pre-Ignition, SAE Int. J. Advances & Curr. Prac. in Mobility 7(4):1607-1618, doi:10.4271/2024-01-4290., 2024.

[7] Gschiel K., Wilfling K. & Schneider M., "Development of a method to investigate the influence of engine oil and its additives on combustion anomalies in hydrogen engines.," Automot. Engine Technol. 9, 3, 2024.

[8] Lurf G., Murakami S., Jocham B. et. al., "Mitigating Lube Oil Ignition and Realted Flame Propagation through Combustion Parameter Optimization in Hydrogen Engines," in *14. Dessauer Gasmotoren-Konferenz*, Dessau, 2026.

[9] Grabner, P., Schneider, M., and Gschiel, K., "Formation Mechanisms and Characterization of abnormal Combustion Phenomena of Hydrogen Engines," in *2023 JSAE/SAE Powertrains, Energy and Lubricants International Meeting*, Kyoto, Japan; https://doi.org/10.4271/2023-32-0168, 2023.

[10] Plöckinger S., Kappacher P., Schutting E., Trapp, C., "Combined numerical and experimental study of mixture formation strategies and their impact on anomalies in heavy-duty PFI hydrogen ICE.," in *Thiesel 2026 Conference on Thermo-and Fluid Dynamics of Clean Propulsion Powerplants*, Valencia, 2026.

[11] Li Y., Gao W., Zhang P., Fu Z. et.al., Influence of the equivalence ratio on the knock and performance of a hydrogen direct injection internal combustion engine under different compression ratios, International Journal of hydrogen energy 46, 11982-11993, 2021.
[12] Gschiel K., Analysis and Measures to reduce Combustion Anomalies on a turbocharged Hydrogen Engine with internal Mixture Formation, Dissertation, Graz University of Technology, 2025.
[13] Christoforetti P., Transient behaviour optimization of hydrogen internal combustion engines, Dissertation, Graz University of Technology, 2026.

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

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Abstract: Hydrogen is a 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. Specifically, when it comes to power limitations due to combustion anomalies such as pre-ignition and knock. Abnormal combustion remains a key limiter for hydrogen-fueled Internal Combustion Engines (H_2 ICE), especially during warm weather operations and particularly at low speed and high load operation, aka Low-Speed Pre-Ignition (LSPI) conditions. While lubricant chemistry has been optimized to influence LSPI in gasoline GDI engines, the dominant drivers in H_2 ICEs are much less established. This contribution isolates lube oil formulation effects on combustion anomalies using Liebherr H_2 ICE through experimental results during steady state and transient operation. Motivated by H_2 ICE performances increase, a specific lubricant formulation is being co-developed with an external partner.

The Liebherr 4-cylinder 9,0 liters H_2 ICE is equipped with a port-fuel injection system and dual-stage turbocharging system. The combustion takes places within lambda range of 1,5 to 4,0 depending on the specific operating conditions. Beyond efficiency and emissions, the off-highway sector demands high dependability: Liebherr targets combustion-anomaly-free operation across diverse ambient conditions for at least 15'000 operating hours without power derating or mechanical failure, making reliability a primary design objective alongside performance.

Beyond test-bench work, some prototype hydrogen-fueled Liebherr wheel loaders equipped with the 4-cylinder 9,0 liters H_2 ICE are deployed with end customers in operating quarries in Germany and Austria, where they operate under production workloads, seasonal variations and high-dust environments. These customer trials provide in-service evidence of combustion anomaly resistance, complementing test bench results and guiding lubricant formulation for dependable off-highway operation.

A test procedure was specifically developed at Liebherr Machines Bulle in Switzerland to evaluate various lube oil composition on back-to-back basis in engine test bench during steady-state and transient operation. During steady-state characterization at high-loads several thousands of combustion cycles per cylinder were collected under nominal and warm boundary conditions. Impact of the lube-oil formulation was determined by an

evaluation of abnormal combustion statistics. A similar approach during transient tests was also assessed.
The main results give details about the base-oil and lube oil additive contents such as calcium, magnesium and molybdenum. Liebherr engineering team evaluated several lube oil candidates in addition to the reference lube-oil. Within the various lube oil tested the base group, lube oil viscosity and molybdenum enrichment emerges as one of the primary levers to reduce combustion anomalies especially at low speeds whereas calcium and magnesium levels exhibit minor influence. Base lube oil group changes alone were insufficient to provide significant impact on combustion anomalies. These findings align with literature indicating minimal calcium and magnesium content and a pronounced molybdenum benefit for pre-ignition and knock mitigation in H_2 ICEs.
In line with the fundamental chemistry of hydrogen combustion, we emphasize that CO_2 and CO measured at the exhaust of H_2 ICEs originate from lube oil consumption and not from the fuel itself. Minimizing these lube oil derived carbon emissions is therefore essential to qualify H_2 ICEs as "nearly zero emission" solutions for construction equipment considering CO_2 produced by the engines <=1 g/kWh. Therefore, carbon species in exhaust gas were systematically evaluated throughout the test campaign. CO_2 and CO emissions were compared across the various lube oils.
Implications for off highway H_2 ICE development show that an additive driven strategy with higher molybdenum could potentially deliver significant combustion anomalies reduction at low speeds, if viscosity related friction penalties and protection against corrosion are managed.

Keywords: hydrogen internal combustion engine, H_2 ICE, off-highway machinery, lubricant formulation, combustion anomalies, knock, pre-ignition, oil consumption, carbon emissions, Liebherr.

1 Introduction

Decarbonization of heavy-duty off-highway machinery requires technical solutions that combine low or zero carbon operation with the power density, durability and operational flexibility expected from conventional internal combustion engines. For construction machinery, the replacement of diesel engines by alternative powertrain technologies presents several challenges, including energy storage, machine packaging, robustness, refueling time, ambient-condition capability, cooling requirements and total cost of ownership.

For Liebherr off-road applications, hydrogen internal combustion engines offer several advantages. They provide a near CO_2-free fuel pathway at the point of fuel use, high power density compared with battery-electric solutions, comparable transient performances to existing diesel engines, lower hydrogen purity requirements than fuel cells, reduced sensitivity to vibrations compared to fuel cells, no liquid water emission as encountered with fuel cells, limited H_2 slip compared to fuel cells, competitive cost potential, compatibility with existing machine cooling packages and the possibility of using established after-sales and remanufacturing infrastructures.

Liebherr started hydrogen ICE development in 2019 with a first six-cylinder engine. The first start of the six-cylinder hydrogen engine took place at IAV Gifhorn in December 2020, followed by commissioning of hydrogen test cells at Liebherr Machines Bulle in Switzerland and commissioning of the R9XX H_2 excavator in 2021. Further development milestones included a BAUMA innovation award in 2022, the first start of a Liebherr hydrogen wheel loader in 2024, the beginning of field testing in a quarry in Austria in 2025 and continued development of a four-cylinder engine for wheel-loader applications.

Within this development program, combustion anomalies have been identified as a key technical challenge. Hydrogen's wide flammability limits, low ignition energy and high flame speed make the combustion system highly sensitive to local ignition sources, mixture preparation, residual gas management, component temperatures and oil transport into the combustion chamber. This paper focuses on the role of lubricant formulation as a lever to mitigate such combustion anomalies in a Liebherr off-highway hydrogen-fueled ICE.

2 Liebherr hydrogen ICE

The engine investigated in this work is the Liebherr H964 hydrogen engine, a four-cylinder, in-line, 9.0-litre engine operated on 100 % hydrogen. The engine has a bore of 135 mm and a stroke of 157 mm.

The hydrogen engine uses a Liebherr port fuel injection system with an inlet pressure of 25 bar. The combustion system includes steel pistons with a dedicated bowl shape, a specific compression ratio and a dedicated piston-ring package. The valve train uses dedicated cam profiles with reduced overlap. The air path is based on a two-stage turbocharging system with air-to-water coolers and electronic wastegate control, combined with a low-volume intake manifold and intake throttle. Engine control is performed by a Liebherr ECU with in-house developed software. Spark ignition is provided by a capacitive ignition controller with dedicated M14 iridium spark plugs and variable spark profile.

The engine also integrates a passive closed crankcase ventilation system with a filter element, two knock sensors mounted on the engine block and a specific lubricant developed with an external partner. The combination of hydrogen-specific combustion hardware, control software, boosting system, knock detection and lubricant development forms the foundation of the engine concept investigated in this paper. https://liebherr-my.sharepoint.com/personal/vincent_boucand_liebherr_com/Documents/Microsoft Copilot Chat Files/IAV Spark 2026 - Liebherr H2 ICE - 20260702.pdf



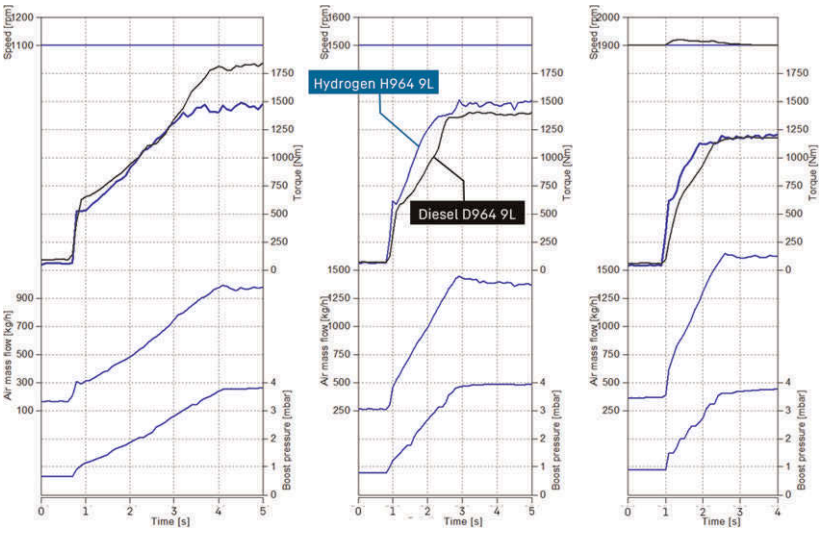
H964 engine cold side



H964 engine hot side

In terms of full-load performance, the hydrogen H964 reaches a rated power of 230 kW, which is similar to the comparable to the diesel D964 power range of 200–230 kW. The maximum torque of the hydrogen engine is 1500 Nm, compared with 1500–1965 Nm for the diesel variants. The maximum BMEP of the hydrogen engine is 21 bar between 1100 and 1400 rpm, while the diesel version reaches up to 27.5 bar at 1100 rpm for a specific application.https://liebherr-my.sharepoint.com/personal/vincent_boucand_liebherr_com/Documents/Microsoft Copilot Chat Files/IAV Spark 2026 - Liebherr H2 ICE - 20260702.pdf

Transient performance is a central requirement for off-highway applications. Liebherr's four-cylinder hydrogen ICE demonstrated a transient response comparable to the equivalent diesel engine, supported by the high-performance boosting system and innovative engine control system. The transient capability fulfills the requirements of Liebherr off-road applications such as wheel loaders and excavators.



H964 engine transient performances during load steps

3 Application context and field test operation

The target application presented is the Liebherr L566 H wheel loader. The machine has a weight of 26 tons and a payload capacity of up to 9 tons. Its hydrogen storage system consists of three carbon-fiber tanks at 700 bar, providing 34 kg of usable hydrogen. The hydrogen pressure at the engine inlet is 25 bar, and cold-start ability has been tested on machine and cold test bench down to -15 °C. Wheel loaders are considered among the most transient applications in Liebherr's machine portfolio.

Field testing of the hydrogen wheel-loader machine is being carried out by customer Strabag in Austria over a two-year operation period. The machine is expected to save up to 100 tons of CO_2 per year, corresponding to approximately 37500 liters of diesel. A hydrogen filling station has been built on-site to refuel the wheel loader at the quarry.



Liebherr L566H wheel loader

At the time of the presentation, the H964 engine development program had accumulated 8361 hours on engine test benches at Liebherr Machines Bulle SA in Switzerland. Field-test machines in Austria had also started accumulating operating hours.