EVALUATION OF JETFIRE® PRE-CHAMBER IGNITION FOR LEAN, DI HOMOGENEOUS CHARGE, HEAVY FUELED COMBUSTION AND MULTI-FUEL CAPABILITY

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Acknowledgement

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Outline

Introduction

- Single Fuel Strategy and SI Challenges
- Jetfire® Pre-chamber Ignition

Experimental Setup

- Engine Specifications
- Fuels Tested
- Combustion Analysis Parameters

Results and Discussion

- Kerosene-based Fuel - CN30 and CN50
- Compression Ratio Comparison using CN30
- Gasoline (AKI 87, E10)
- Hydrogen

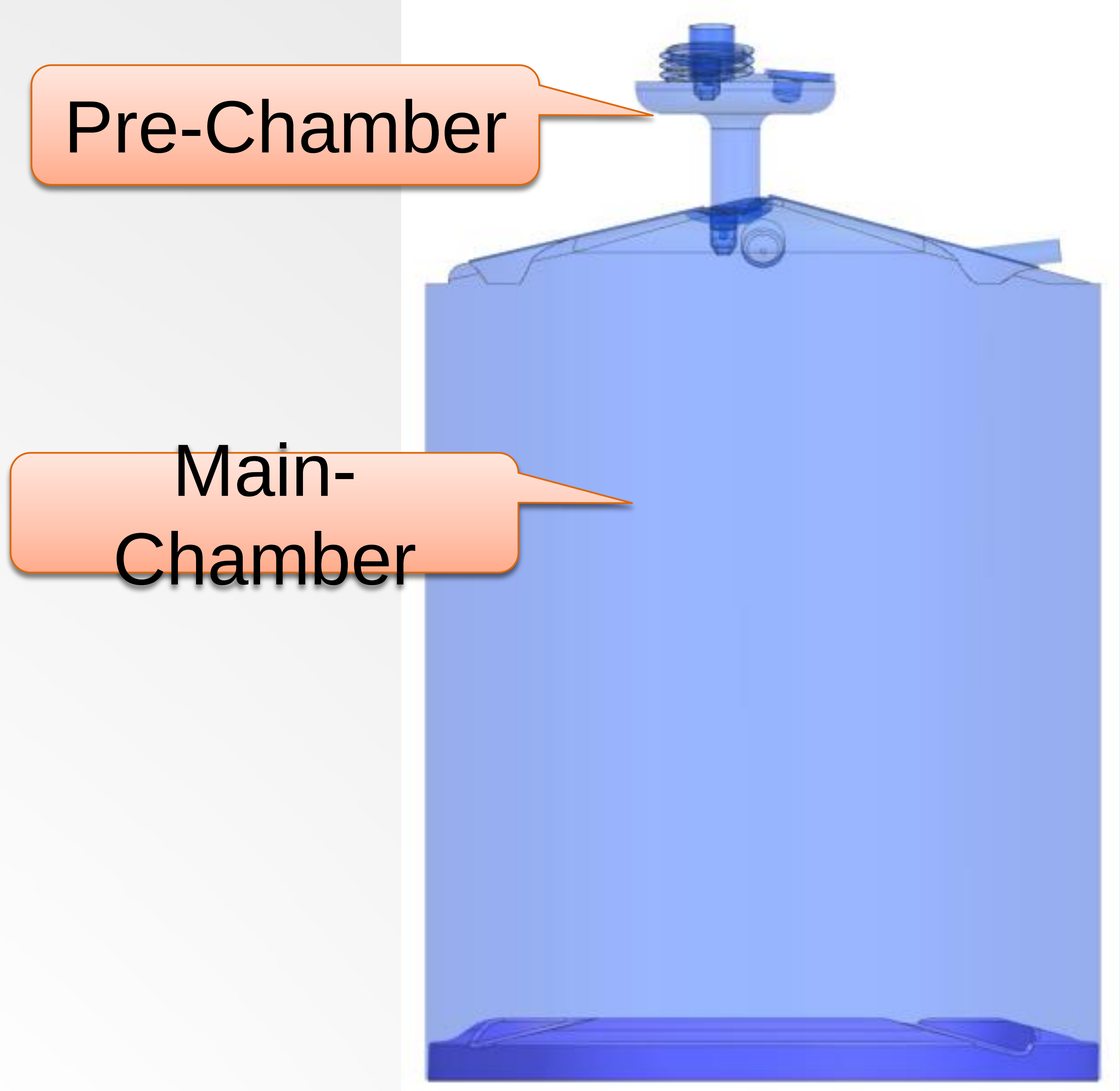
Conclusions and Future Work

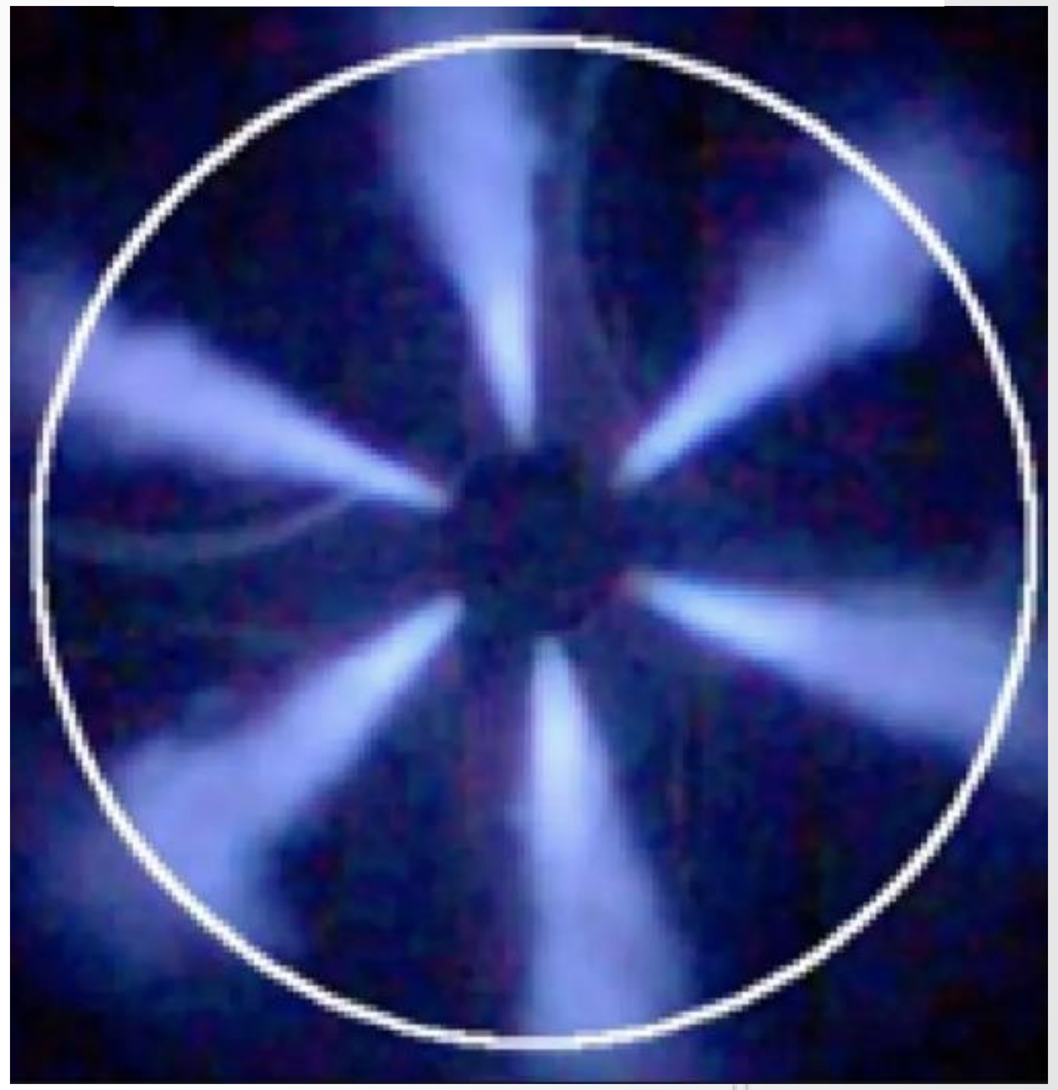
Introduction – Single Fuel Strategy and SI Challenges

- The US military *single fuel strategy* requires military vehicles and auxiliary power units to operate on JP-5, JP-8, and F-24 fuels [1].
- Certain applications favor spark ignition (SI) powertrains over compression ignition (CI).
  - E.g. where high power-to-weight ratios are required.
- Spark ignition of kerosene-based fuels presents challenges due to poor atomization characteristics, slow burn rates, and knock propensity [2].
  - Often, a rich air-fuel mixture is used to promote reliable ignition and mitigate knock [3-5].
- A high-energy ignition system can promote reliable ignition and accelerate the combustion process.

Introduction – Jetfire® Pre-chamber Ignition

- Pre-chamber systems provide a high-energy ignition source for internal combustion engines.
- Consists of a small combustion volume within the engine cylinder head.
  - Combustion is initiated using a spark plug in the pre-chamber.
  - Produces turbulent jets which subsequently ignite the main chamber.
- High energy ignition systems can offer advantages for a variety of fuels and applications:
  - Enable reliable ignition of lean and highly dilute mixtures.
  - Accelerates burn rate for high-efficiency operation.





Introduction – Jetfire® Pre-chamber Ignition

- Jetfire® is a variant of an *active* pre-chamber ignition system.
  - I.e., contains a fuel injector within the pre-chamber.
- Compressed air is delivered via an air scavenge (or “purge”) valve that is actuated shortly before ignition.
- The air scavenge valve removes exhaust residuals from the previous cycle and helps to keep the nozzle cool.
  - Helps to prevent oxidation of the pre-chamber nozzle.
- With heavy fuel, pre-chamber air delivery likely also helps with fuel atomization.
- With gasoline, Jetfire® is particularly well suited for operation with high rates of exhaust gas recirculation (EGR).
  - Pre-chamber ignition quality is maintained at high main chamber dilution rates.

Figure: Jetfire® Pre-Chamber Cartridge

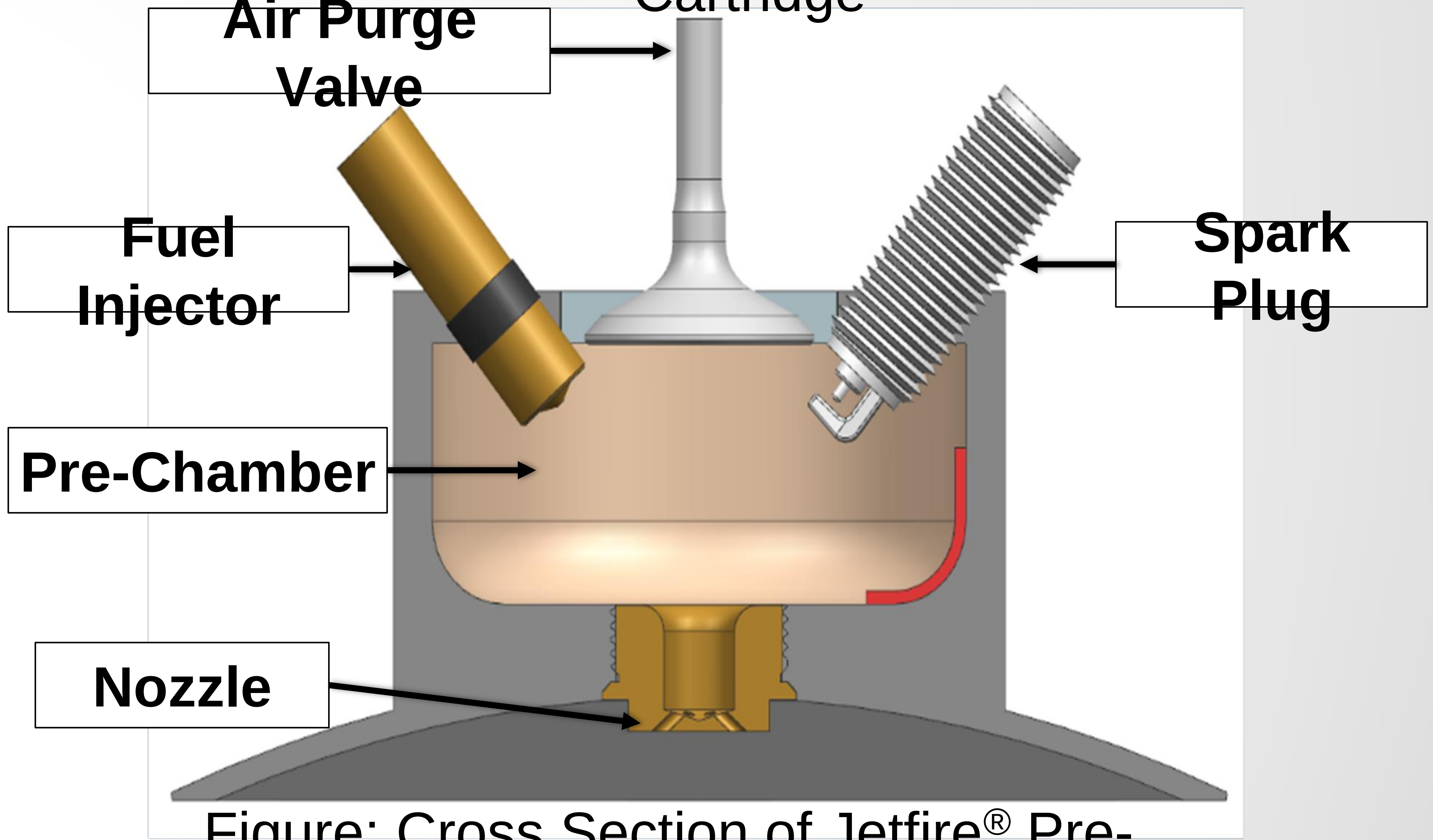


Figure: Cross Section of Jetfire® Pre-Chamber

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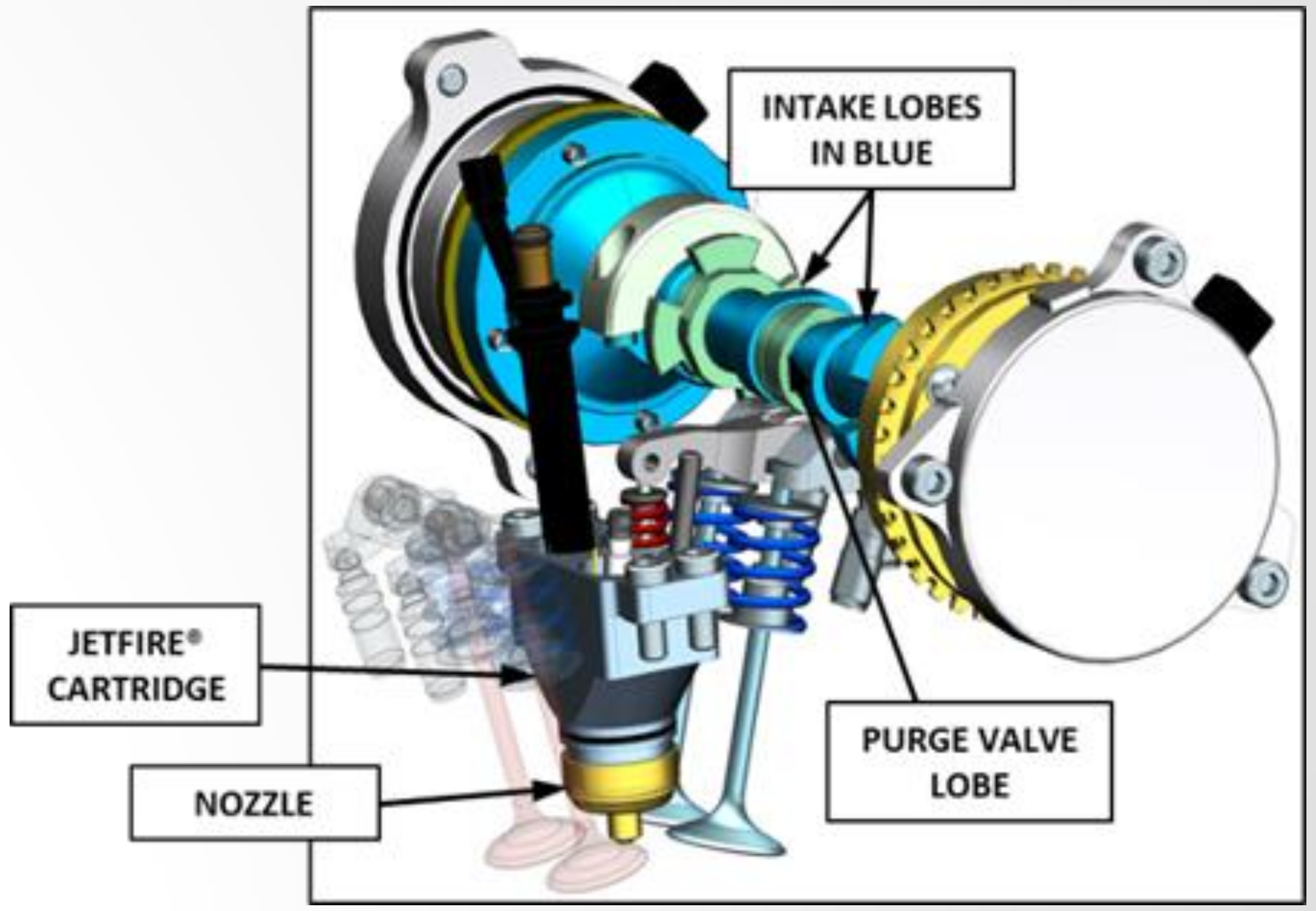
Experimental Setup – Engine Specifications

- Single-cylinder test engine equipped with the Jetfire® pre-chamber ignition system.
- Compression ratio of 7:1 or 8:1 for heavy fuels, and 15:1 for gasoline and hydrogen.
  - Varied via shims underneath the cylinder head.
- Direct injection (DI) within the pre-chamber and the main chamber when running heavy fuel or hydrogen.
  - Port fuel injection in the main chamber when running gasoline.
- Injection within the main chamber occurred during the intake stroke.
  - The objective was to achieve a homogenous mixture.

Parameter	Value
Bore	86.00 mm
Stroke	95.00 mm
Connecting Rod Length	170.00 mm
Compression Ratio	7:1, 8:1, or 15:1
Pre-Chamber Volume	2712 mm^3
Swept Volume	0.552 L
Fuel Injection	100 Bar (Both Chambers)



Experimental Setup – Fuels Tested

Heavy Fuel:

- Two fuels kerosene-based fuels provided by the Army Research Lab.
  - One with a cetane number of 30 (CN30) and another with a cetane number of 51 (CN50).
- Objective: demonstrate the feasibility of these fuels for use with Jetfire® ignition, and performance comparison of the two fuels.

Gasoline:

- AKI 87 octane gasoline with 9.8% ethanol.
- Objective: Examine EGR dilution tolerance, efficiency, and emissions characteristics using Jetfire® ignition.

Hydrogen:

- Compressed hydrogen gas.
- Objective: preliminary demonstration of Jetfire® ignition with hydrogen fuel.

Experimental Setup – Combustion Analysis Parameters

- Gross indicated mean effective pressure:
  - $IMEP_{Gross} = \frac{1}{V_d}\int_{Compression}^{Expansion} PdV$
  - Is a measure of the normalized engine load based on in-cylinder pressure data.
- IMEP coefficient of variation:
  - $IMEP\ COV\ (\%) = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \cdot 100\%$
  - Is a measure of combustion stability.
- Maximum amplitude of pressure oscillation:
  - $MAPO = Max\left|P_{raw} - P_{filtered}\right|$
  - Is a measure of knocking combustion severity.
- Lambda
  - $\lambda = \frac{AFR}{AFR_{stoic}}$

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Results and Discussion: Kerosene-Based Fuel

- Results shown here all used a 7:1 compression ratio.

Observations:

- Both fuels show stable lean operation.
- CN50 generally knock limited beyond 9 bar IMEPg.
  - CN30 can achieve 13 bar IMEPg under elevated manifold pressure.
- CN30 exhibits 1 – 2 percentage points (pp) higher indicated efficiency.
  - Afforded by more optimal combustion phasing due to higher knock resistance.
  - Up to ~5 % lower indicated specific fuel consumption (ISFC).

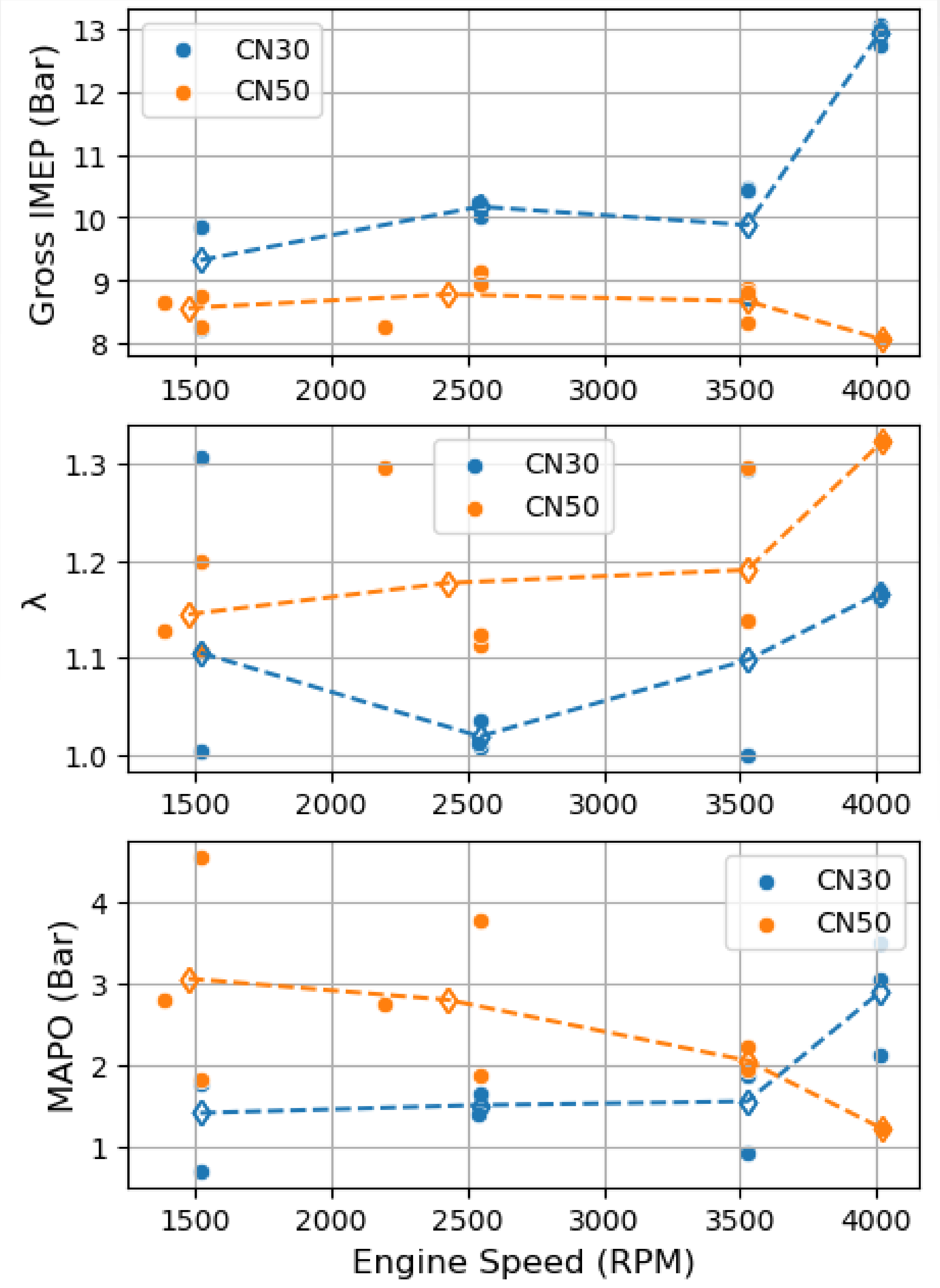

Figure: High Load Points at Various Engine Speeds

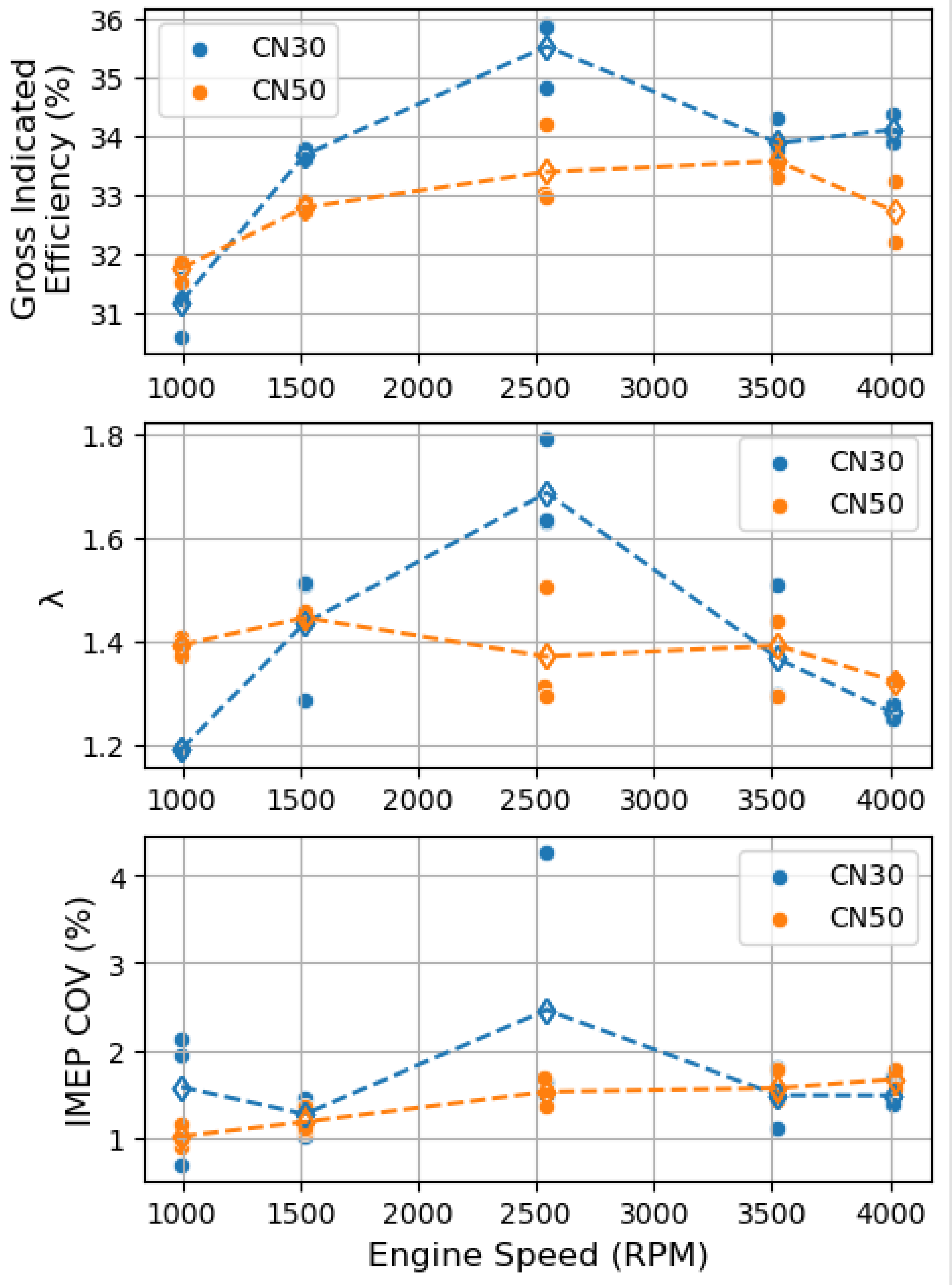

Figure: High Efficiency Points at Various Engine Speeds

Results and Discussion: Compression Ratio Comparison using CN30

- Compared 7:1 to 8:1 CR using CN30 fuel only.
- Results shown are at 2500 RPM.

Observations:

- Fueling could be further reduced with the 8:1 compression ratio.
  - 7:1 – limit λ ~ 1.725
  - 8:1 – limit λ ~2.0
- 8:1 compression ratio yields 5 pp higher indicated efficiency (~11% lower ISFC).
- 8:1 compression ratio exhibits 2-3 bar lower knock-limited load tolerance.

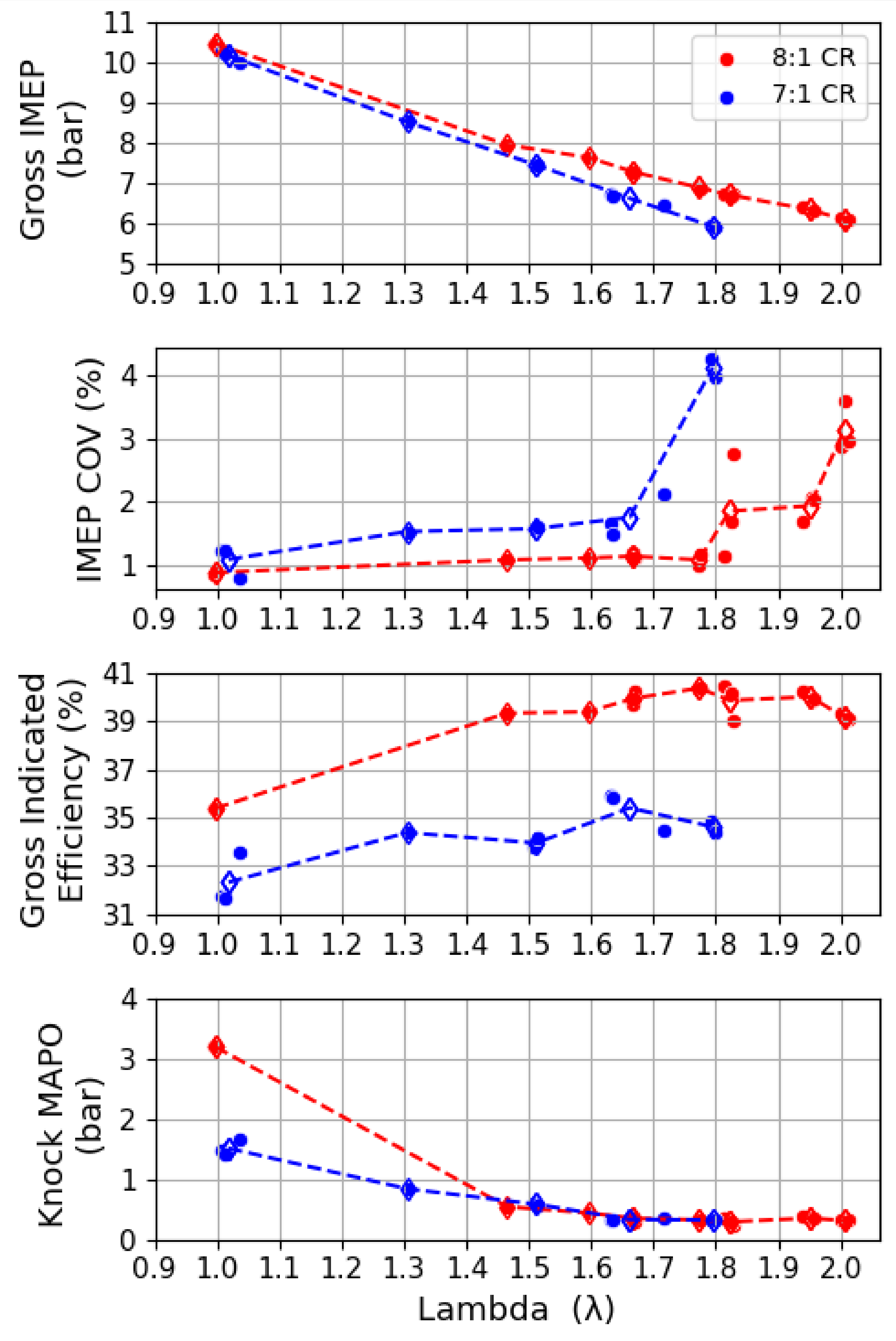

Figure: Compression Ratio Comparison using CN30 Fuel

Results and Discussion: Gasoline (AKI 87, E10)

- All stoichiometric operation using externally cooled EGR.

Observations:

- Dilution tolerance up to ~40% EGR.
- Peak gross indicated efficiency of 48.16% at ~9 bar IMEPg.
- Up to a 98% reduction in NOx emissions with high EGR dilution.
- Increase in hydrocarbon emissions due to reduced combustion efficiency.

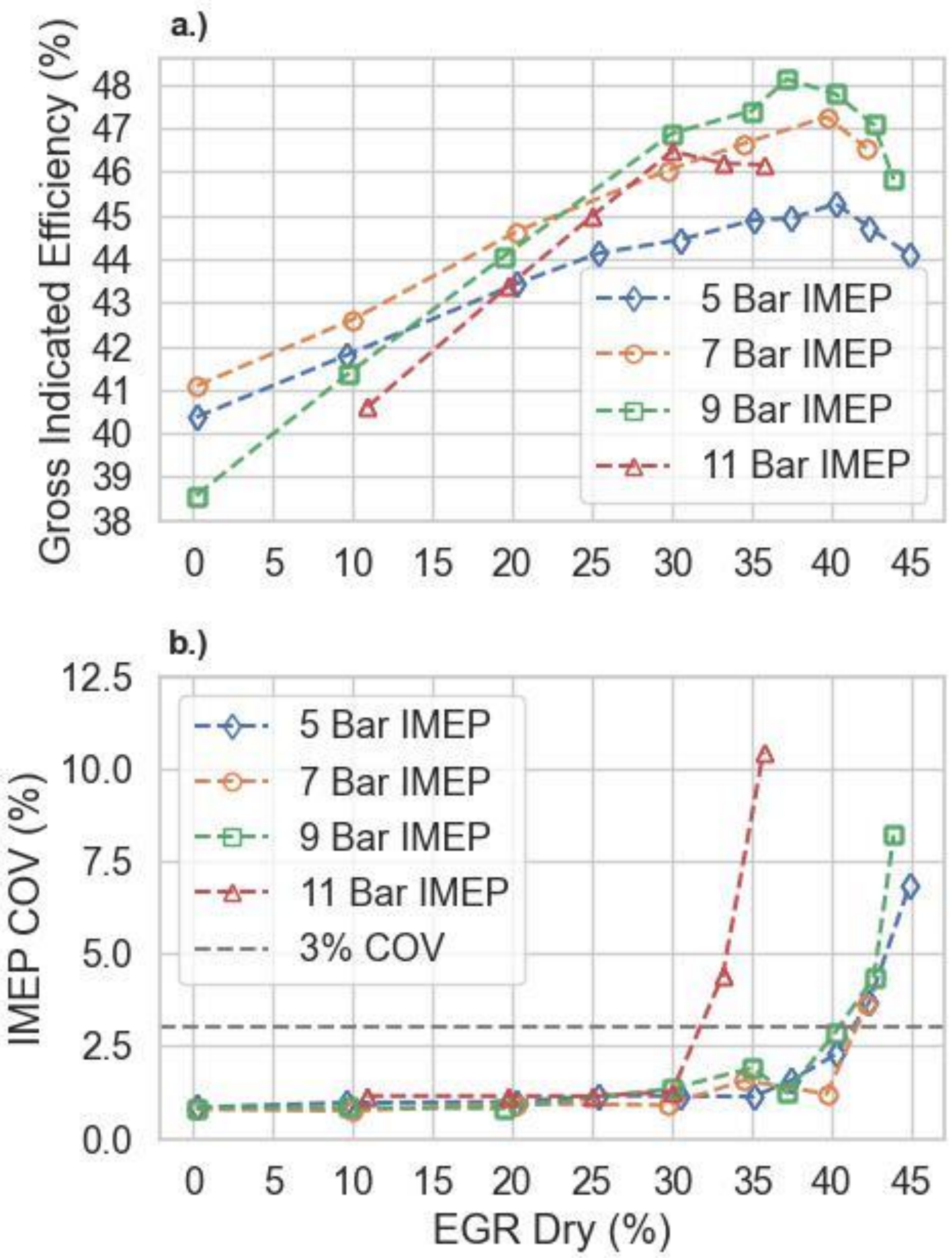

Figure: Indicated Efficiency and IMEP COV Vs. EGR Dilution at Various Loads

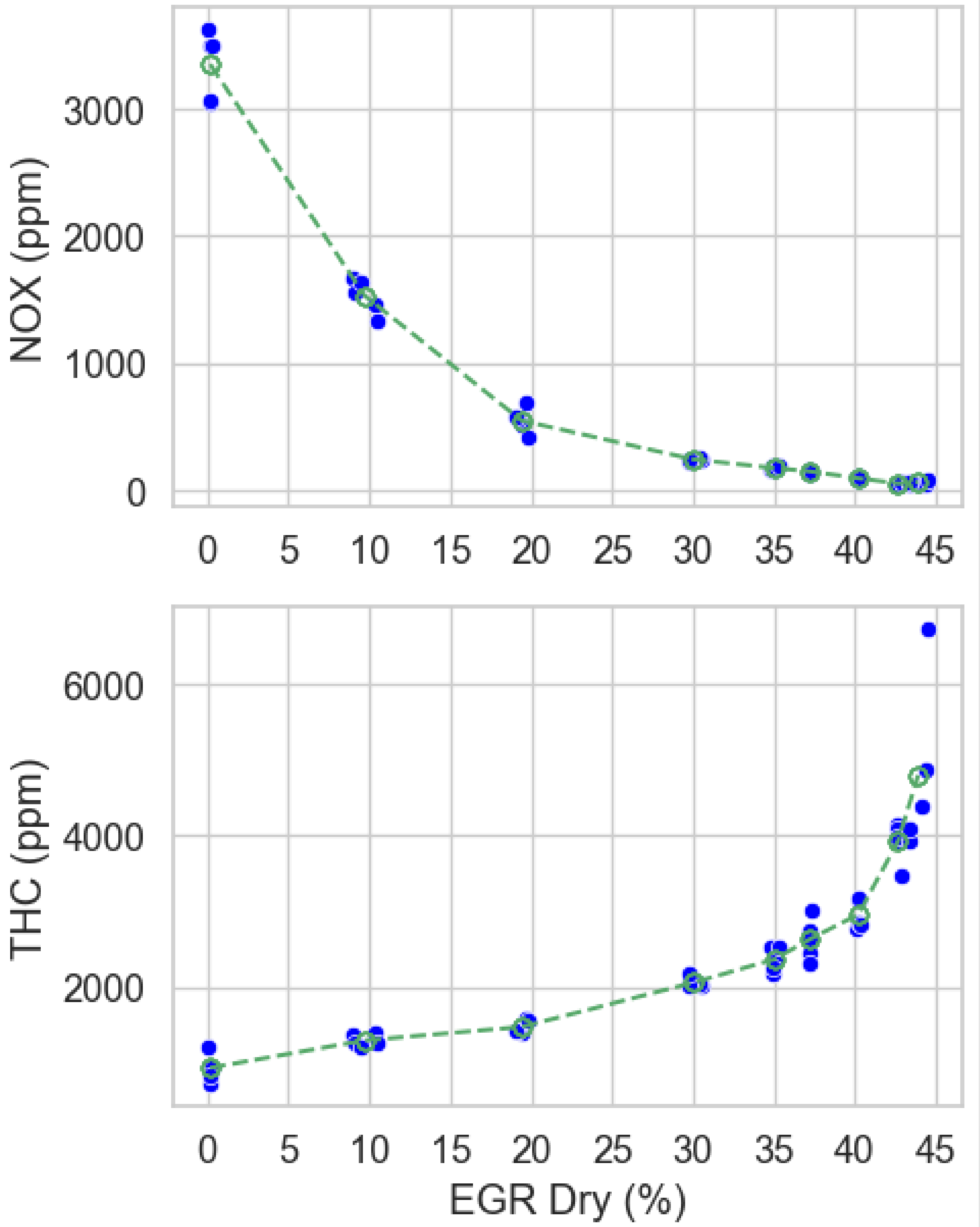

Figure: NOx and total hydrocarbon (THC) emissions Vs. EGR Dilution at 9 Bar IMEPg, 2750 RPM.

Results and Discussion: Hydrogen

- Extremely stable operation with IMEP COV < 1% above 3.5 bar IMEPg.
- Fuel flow rate estimated from experimental injector testing.
- Indicated efficiencies as high as ~49% using the estimated flow rate data.

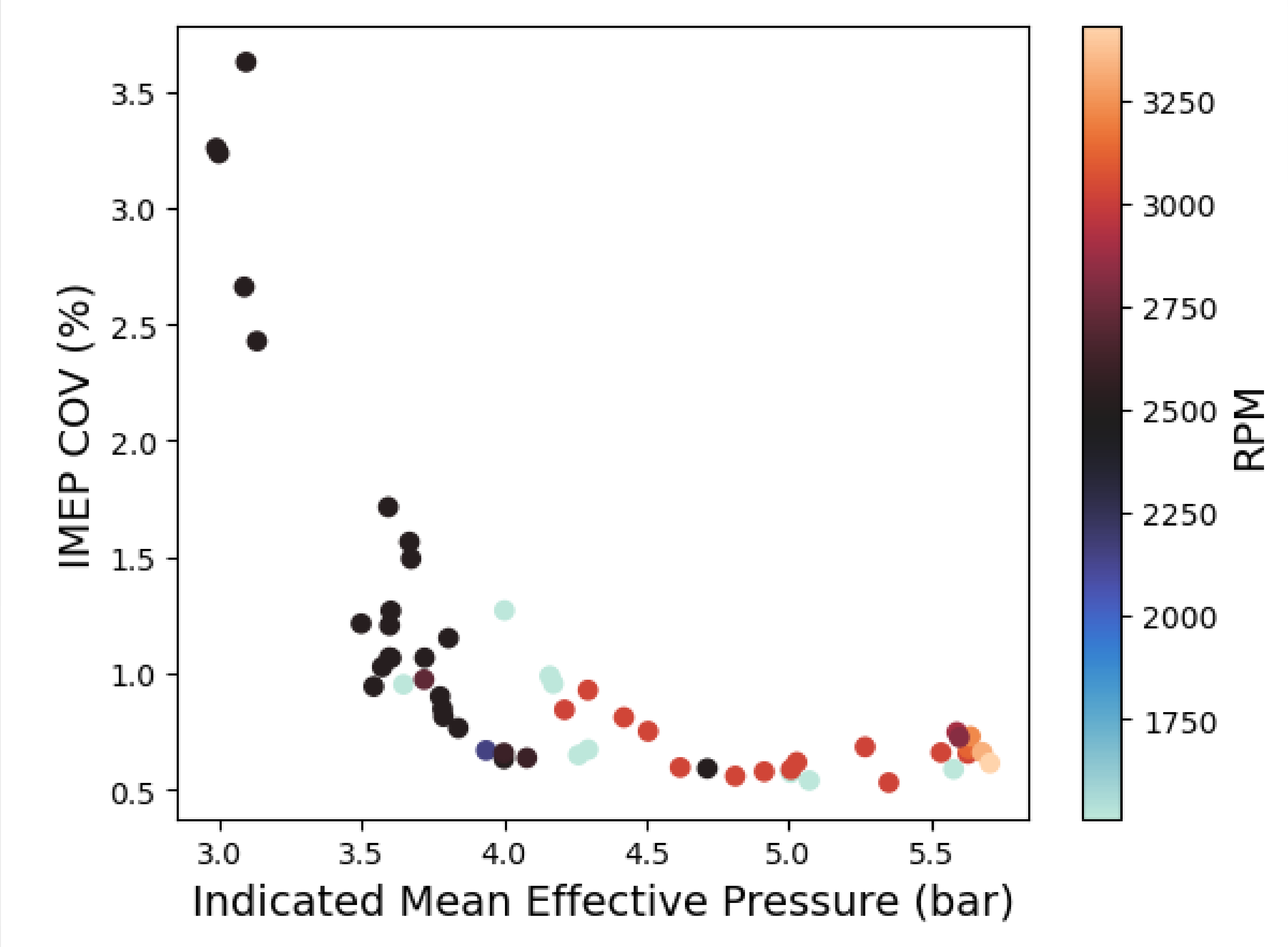

Figure: IMEPg COV Vs. IMEP and Engine Speed Using Hydrogen Fuel

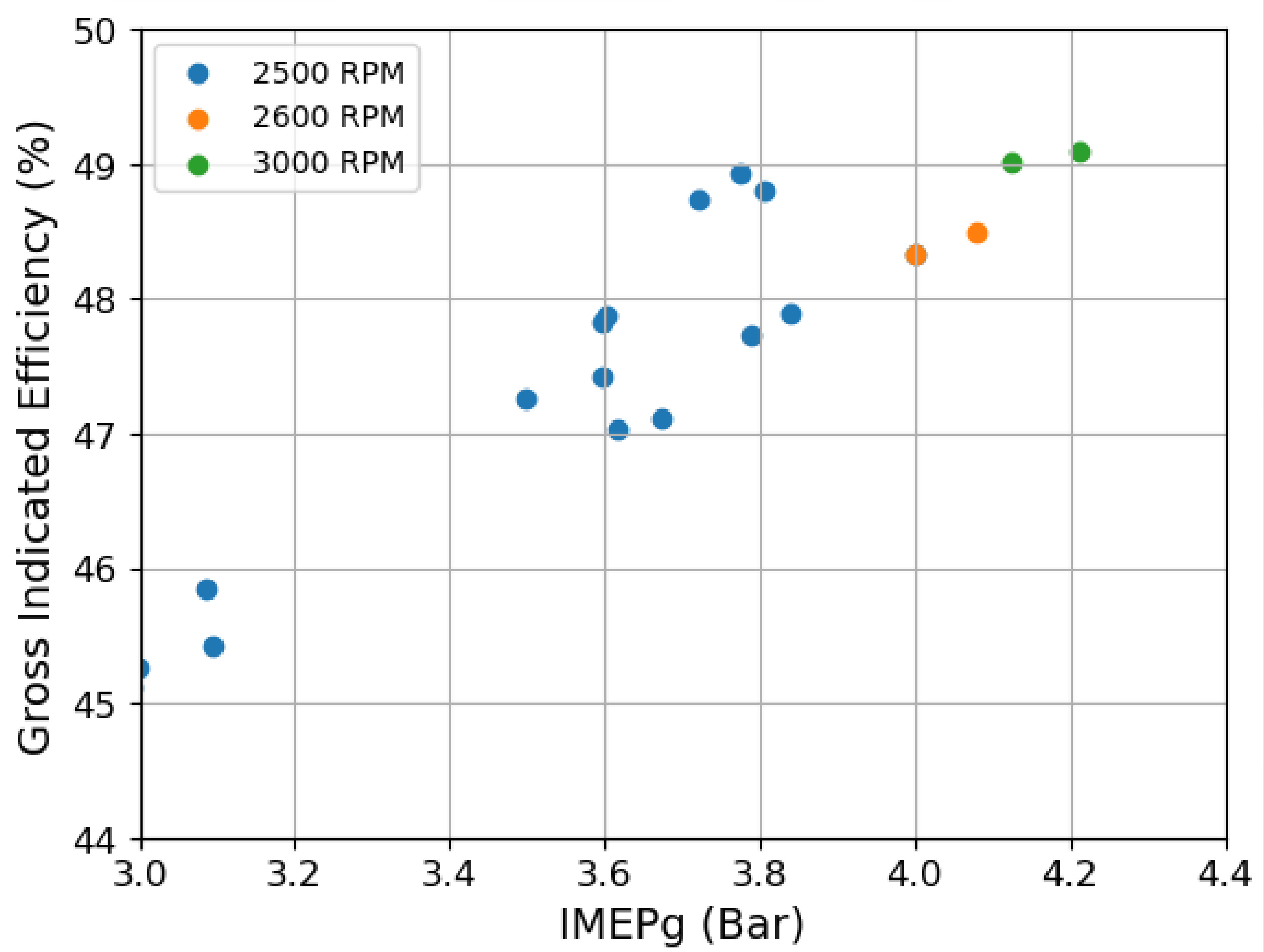

Figure: Estimated Gross Indicated Thermal Efficiency Vs. IMEPg and Engine Speed Using Hydrogen Fuel

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Conclusions

Heavy Fuels:

- Both CN30 and CN50 fuels achieve stable operation from 1000 to 4000 RPM using Jetfire® pre-chamber ignition.
- CN50 was knock limited in excess of 9 bar gross IMEP, while CN30 achieved 13 bar gross IMEP under elevated manifold pressure.
- CN30 fuel tested at a 7:1 and 8:1 compression ratio. Higher compression ratio yields:
  - A 5 percentage point increase in thermal efficiency (~11% decrease in ISFC).
  - A 2-3 bar reduction in peak load capacity.

Gasoline:

- Maximum indicated thermal efficiency of 48.16% achieved under stoichiometric conditions using ~37% EGR dilution.
- NOx emissions may be reduced by up to 98% using Jetfire® ignition with high EGR dilution.
- Hydrocarbon emissions increase due to lower combustion efficiency at high EGR dilution rates.

Hydrogen

- Stable operation with COV < 1% between 3.5 bar and 5.8 bar gross IMEP.
- Estimated efficiency as high as 49%. Required direct flow measurement for validation.

Future Work

- Evaluation of Jetfire® ignition for improved cold start performance.
  - May only need to heat the pre-chamber for cold start.
- Should explore further knock suppression strategies for use with heavy fuels.
  - Sustainable aviation fuels may have a significantly higher cetane number than the fuels tested during this work.
- Transient operation should be explored using gasoline at high EGR dilution.
- Direct hydrogen flow rate will be required to determine efficiency with future testing.

References

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Backup

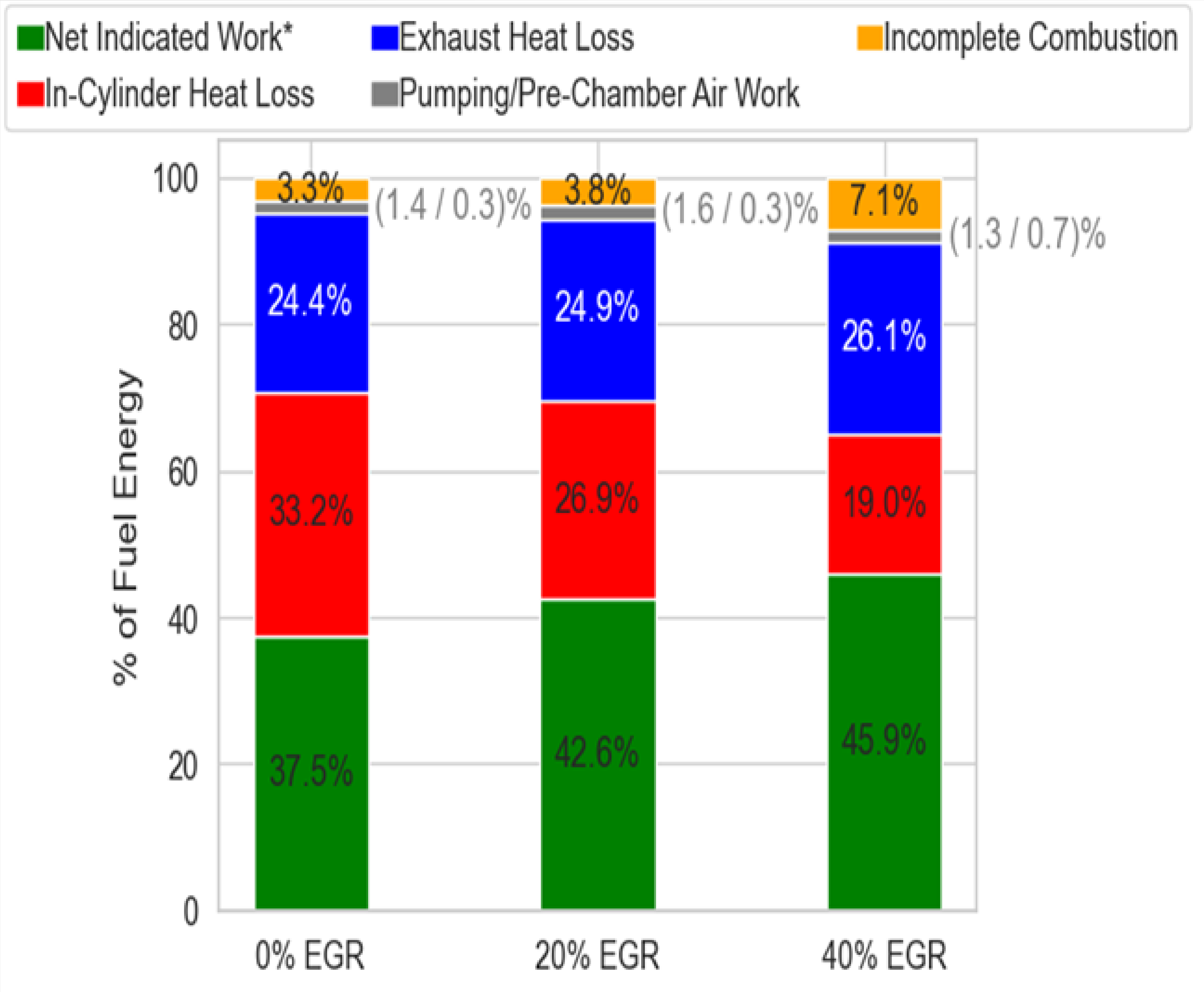

Figure: In-Cylinder Energy Balance Using Gasoline Fuel

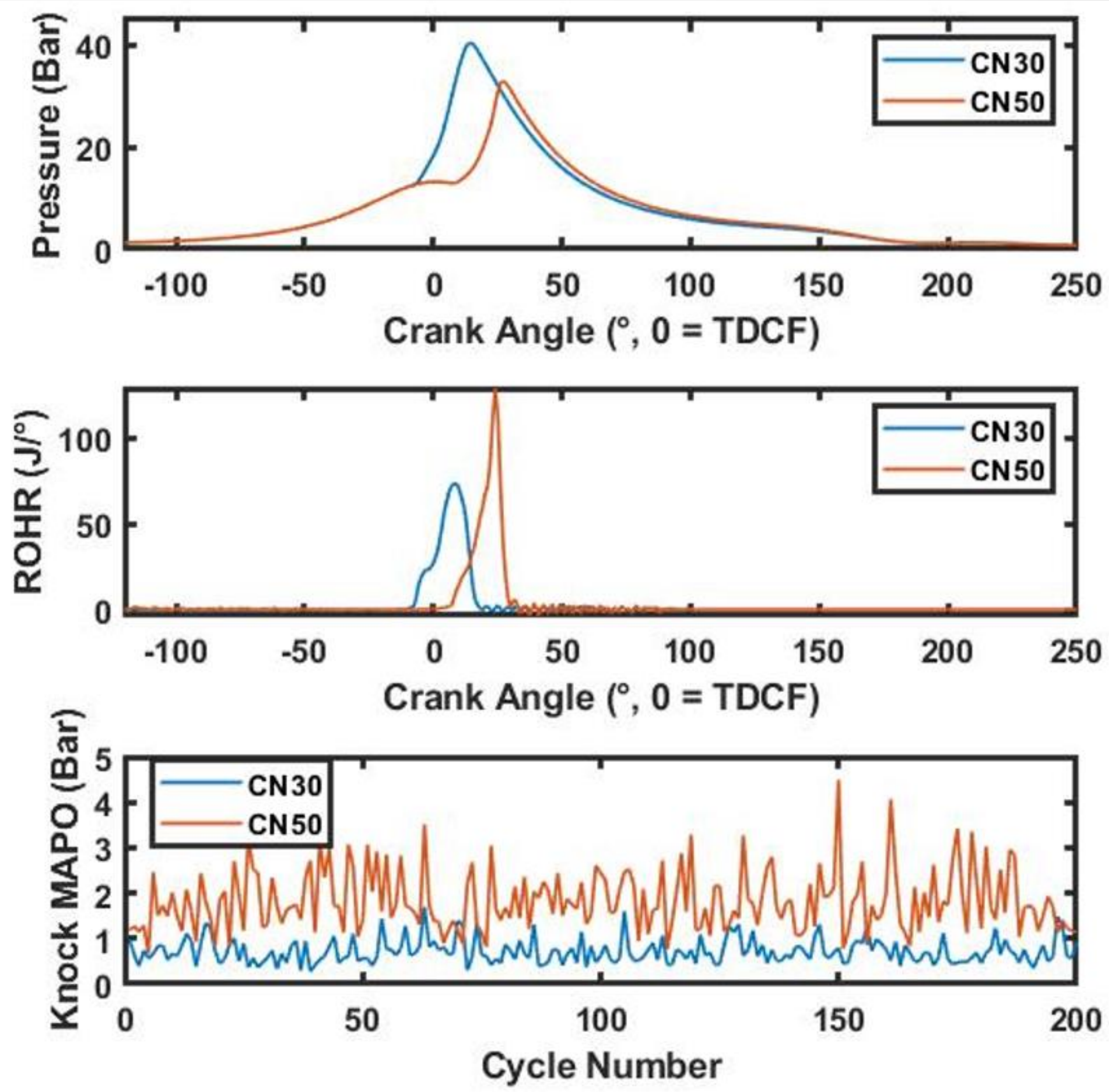

Figure: Main Chamber Pressure, ROHR, and MAPO of CN30 and CN50 Fuels at 1500 RPM and 8.25 bar IMEPg