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May 6, 2025

NH_3 Dual-Fuel Combustion Emissions in a 4-stroke Marine Diesel Engine

Ammonia Combustion Technology Group Meeting

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Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY

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OAK RIDGE National Laboratory NATIONAL TRANSPORTATION RESEARCH CENTER	Co-investigators: Daanish Tyrewala, Scott Curran, Vitaly Prikhodko Support from: Gurneesh Jatana, Derek Splitter, Jonathan Willocks, Scott Palko, Steve Whitted, Jim Szybist, and Scott Sluder [+ Martin Wissink, Chloé Lerin, and Jordan Easter formerly of ORNL]
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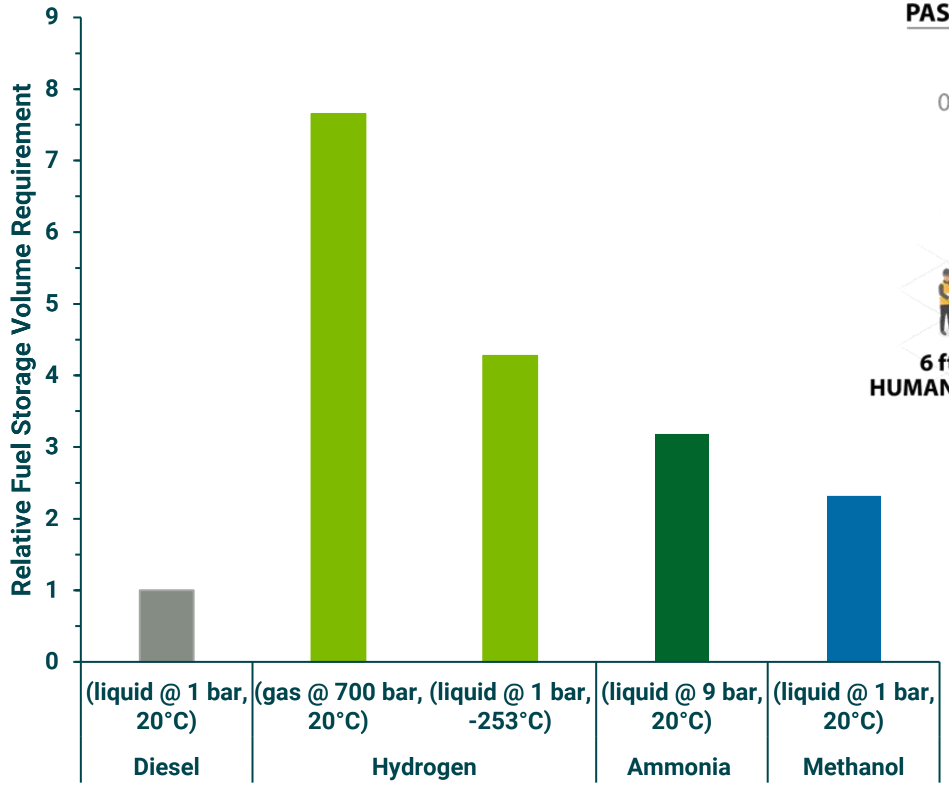
ExxonMobil	Willie Givens for providing lubricating oil and technical support

Why consider ammonia as a marine fuel?

New liquid fuels are being introduced in the marine transportation sector to meet international emissions reduction requirements



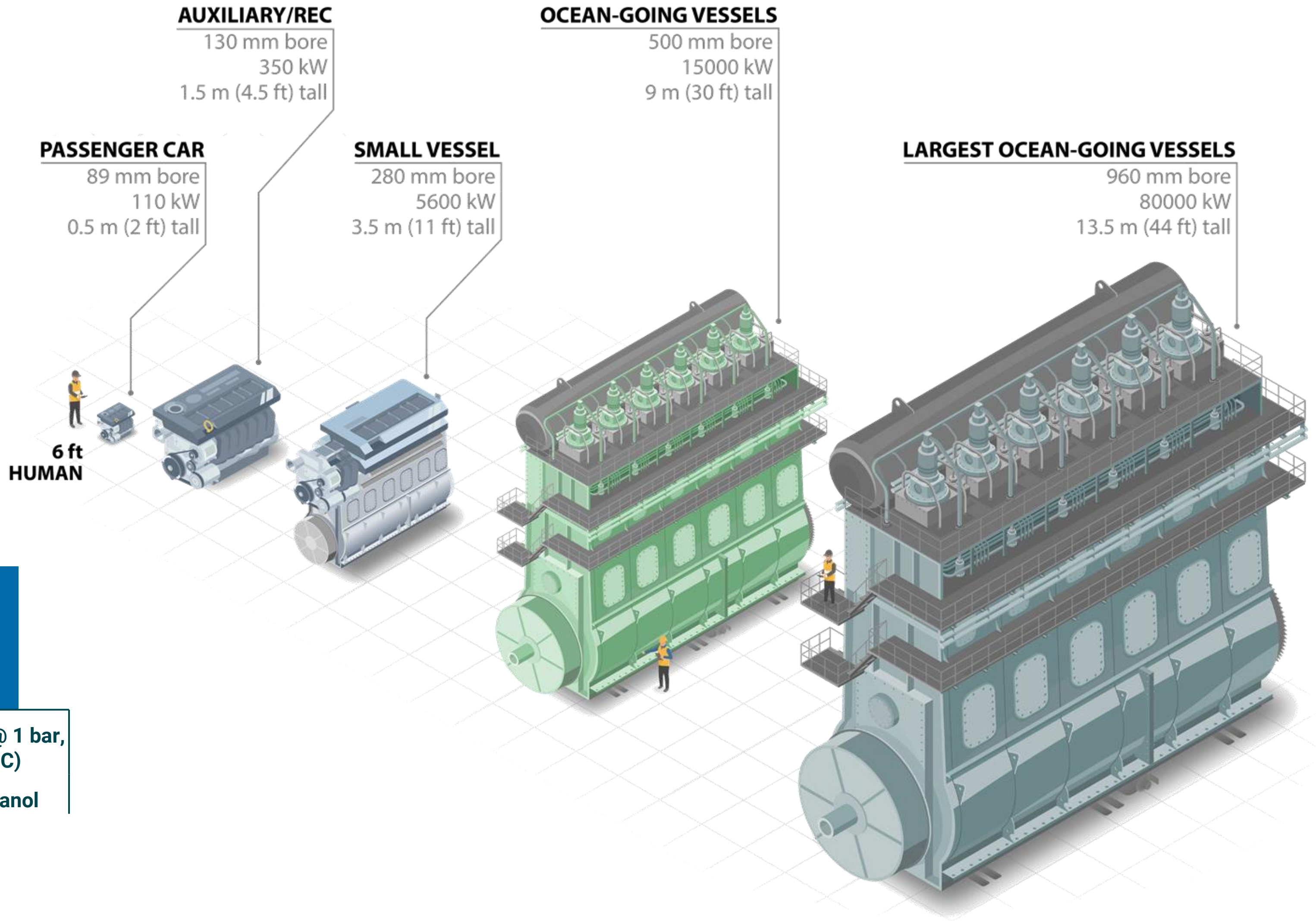
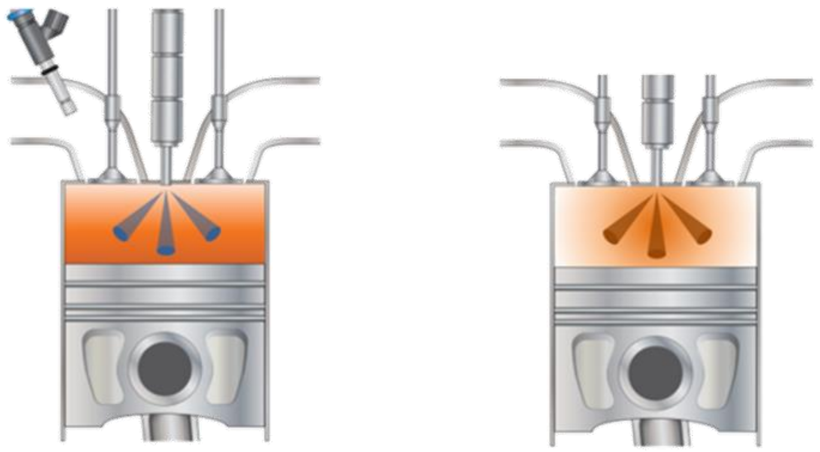


Figure adapted from Curran, et al., "The future of ship engines: Renewable fuels and enabling technologies for decarbonization," *International Journal of Engine Research*, 2023. doi:10.1177/14680874231187954

Non-drop-in alternative fuels (e.g. ammonia, methanol) will be adopted in dual-fuel engines with diesel pilot ignition



Biofuels can be suitable for operation in existing diesel engines (e.g. drop-in)

Other fuels under consideration generally don't auto-ignite well in compression-ignition (diesel) engines

Diesel pilot will effectively ignite pre-mixed or direct-injected alternative fuels

Provides diesel fallback capability if ports don't have alternative fuel available for bunkering

Bio-pilot fuels provide a path for meeting international CO_2 emissions reduction targets

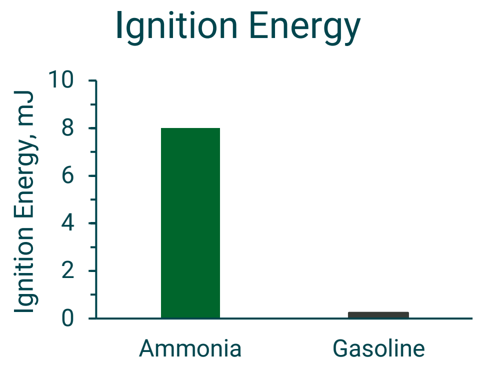
Ammonia has some challenges as an internal combustion engine fuel

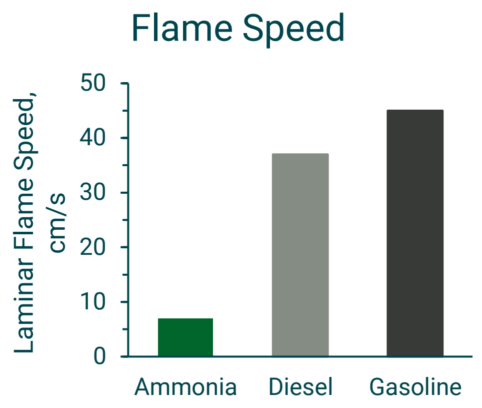
- Health and safety considerations: Ammonia is toxic
  - Widely produced and shipped: established safe handling procedures
  - ORNL has conducted extensive health & safety efforts to enable safe operation[1]

- Challenging fuel combustion properties
  - Doesn't readily auto-ignite: need CR > 30 to operate as diesel fuel
  - Low flame speed, high ignition energy: difficult to burn as spark-ignition fuel

- Emissions control questions
  - Engine-out and aftertreatment-derived N_2O emissions
  - High engine-out NO_x and NH_3 emissions

- Engine component and lubricating oil compatibility
  - Corrosive to copper-containing metals
  - Very different elastomer compatibility from petroleum fuels
  - Lubricant effects are not yet well-understood

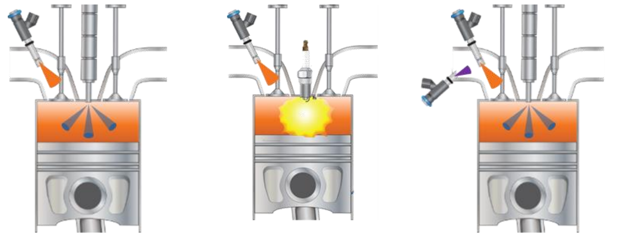


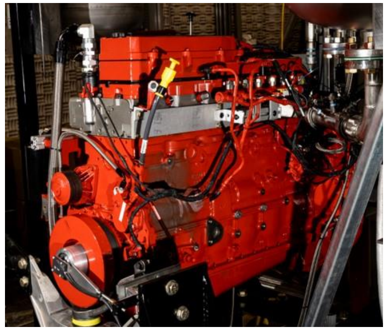


[1]Kaul B, Gillespie T, and Curran S. *Hazard and Operability Study for the Ammonia Fuel Systems at the National Transportation Research Center.* ORNL Report ORNL/TM-2023/2962. doi:10.2172/1989552 https://www.osti.gov/biblio/1989552

Objective: experimentally evaluate ammonia as a fuel for inland and coastal marine engines (including retrofits)

Combustion Strategies

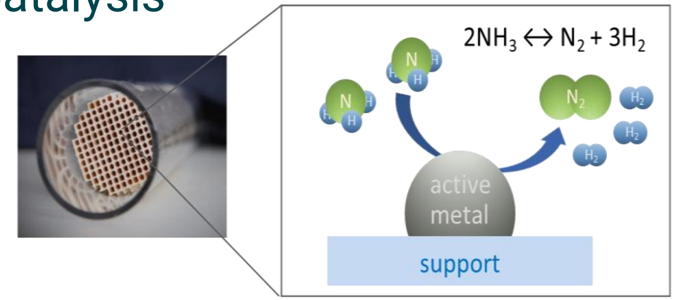




Cummins ISB
6.7L engine

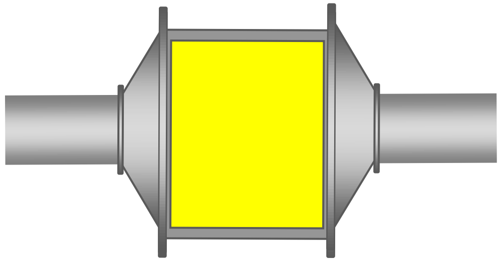
Ammonia
PFI injectors

$NH_3 \rightarrow H_2$ Decomposition Catalysis



Synthetic gas flow reactors

Emissions Controls



Experimental aftertreatment system

SCR: selective catalytic reduction
ASC: ammonia slip catalyst

Developing model validation data at a small scale that can be applied to all scales of engines

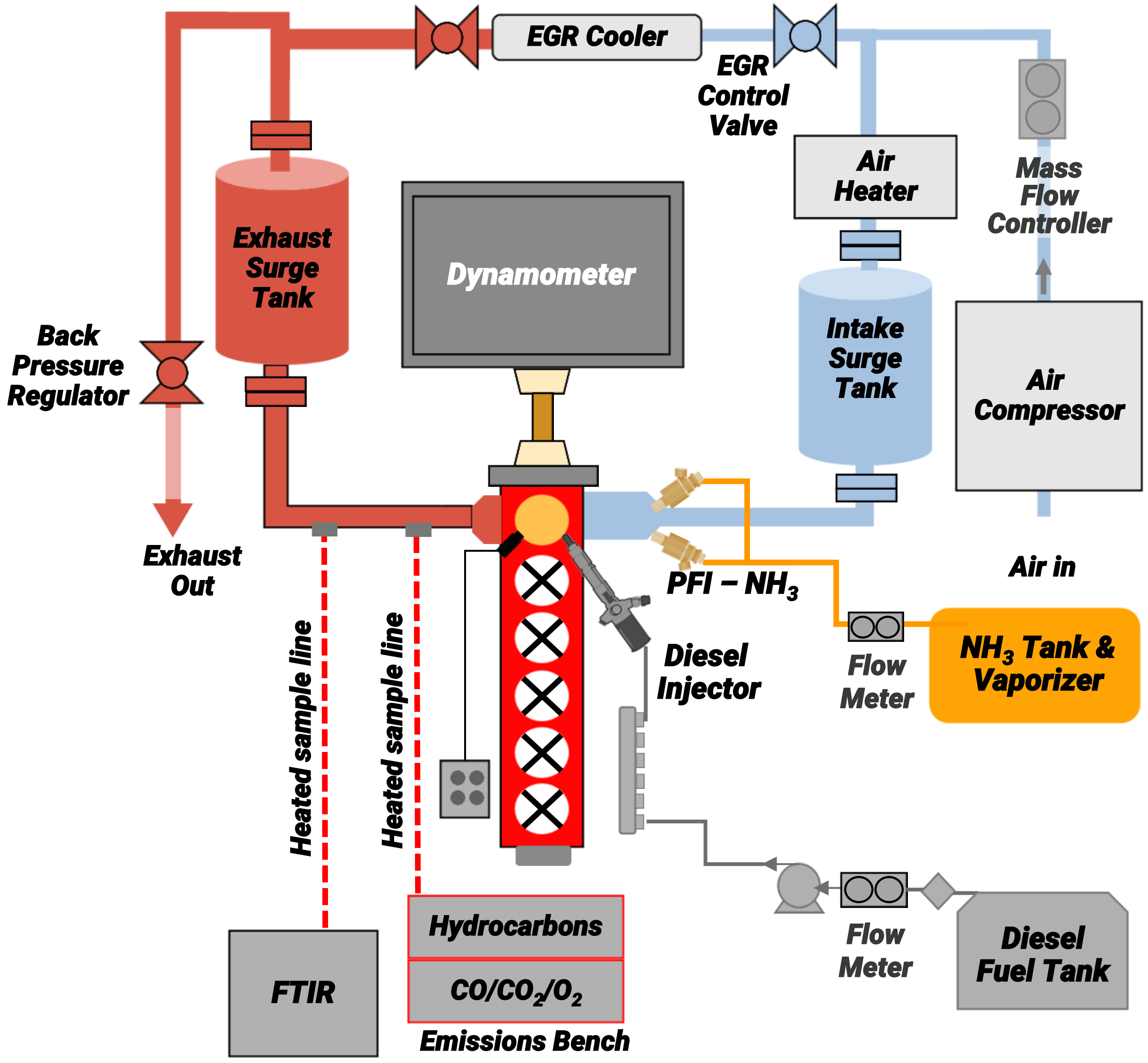
Ammonia dual-fuel experiments were conducted on a single-cylinder Cummins ISB with PFI NH_3 + DI pilot fuel

Engine Specifications

Bore x stroke	107 x 124 mm
Connecting rod length	192 mm
Displacement (1 cyl)	1.12 L
Compression ratio	20:1
Direct injection fuel supply	On-engine high-pressure common-rail pump
Port injection fuel supply	NH_3 cylinder/vaporizer

Pilot fuels:

Ultra-low sulfur diesel (ULSD)
100% FAME Biodiesel (B100)
100% Renewable Diesel (RD)



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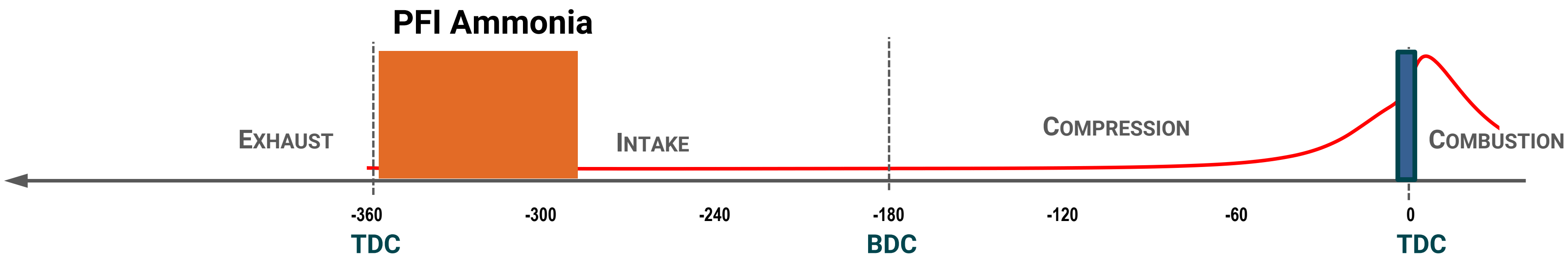
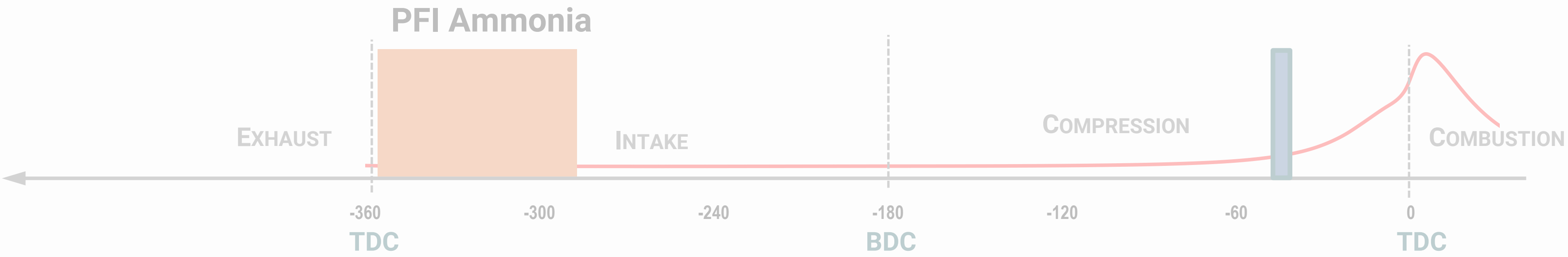
Ammonia dual-fuel direct injection strategies

Low-pressure dual-fuel engine (4-stroke) with direct injection pilot fuel



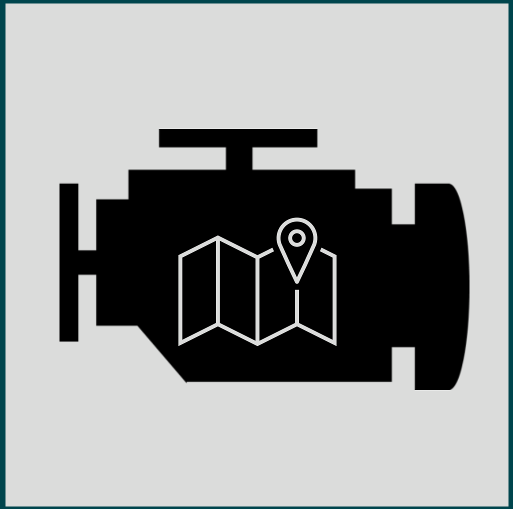
Conventional diesel timing (late pilot)



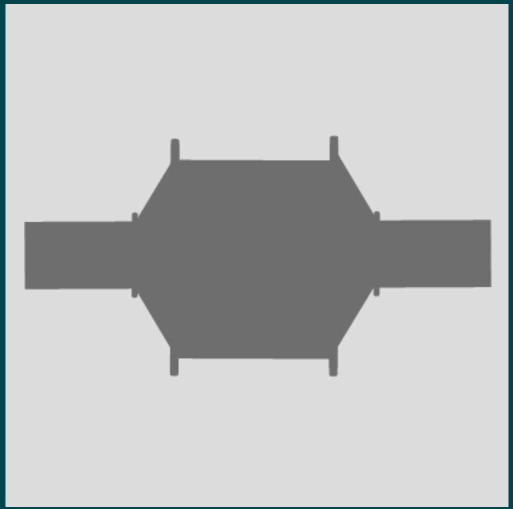
Early pilot

Ammonia Port Injection

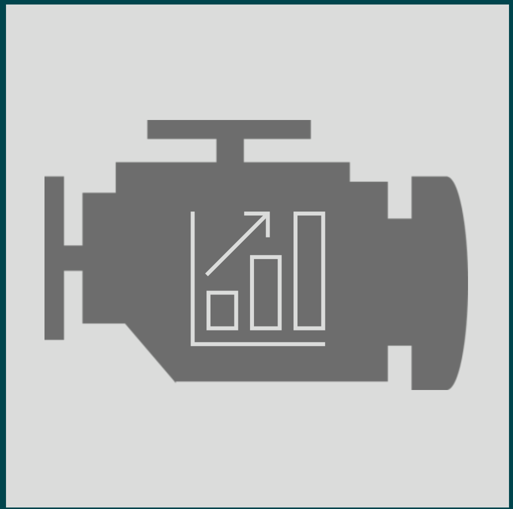
Diesel Direct Injection



Engine Mapping

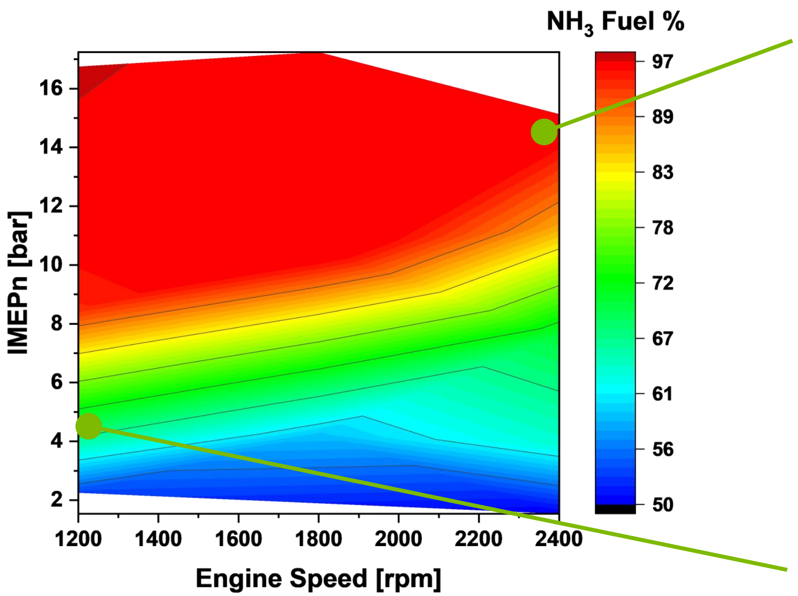


Aftertreatment & Emissions Impacts

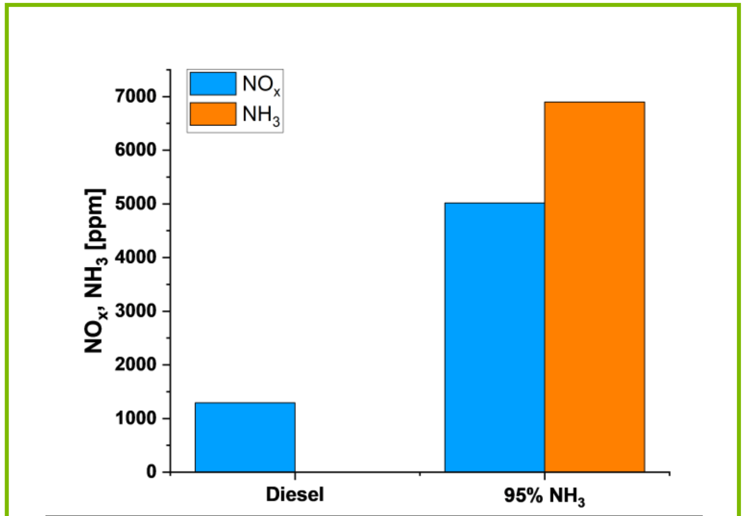


Thermodynamic Efficiency

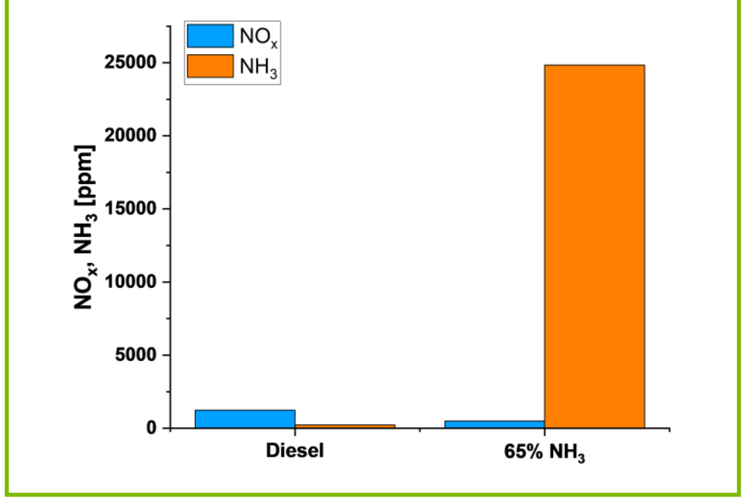
Mapping experiments for dual-fuel NH_3 provide insights into opportunities and challenges for NH_3 combustion in 4-stroke engines

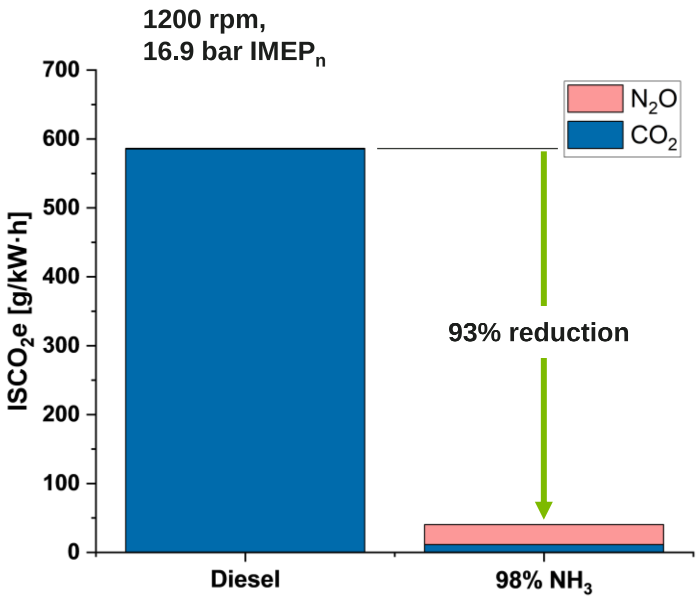


95–98% NH_3 substitution demonstrated at full load



High engine-out NO_x & NH_3





> 90% engine-out GHG reduction at high load

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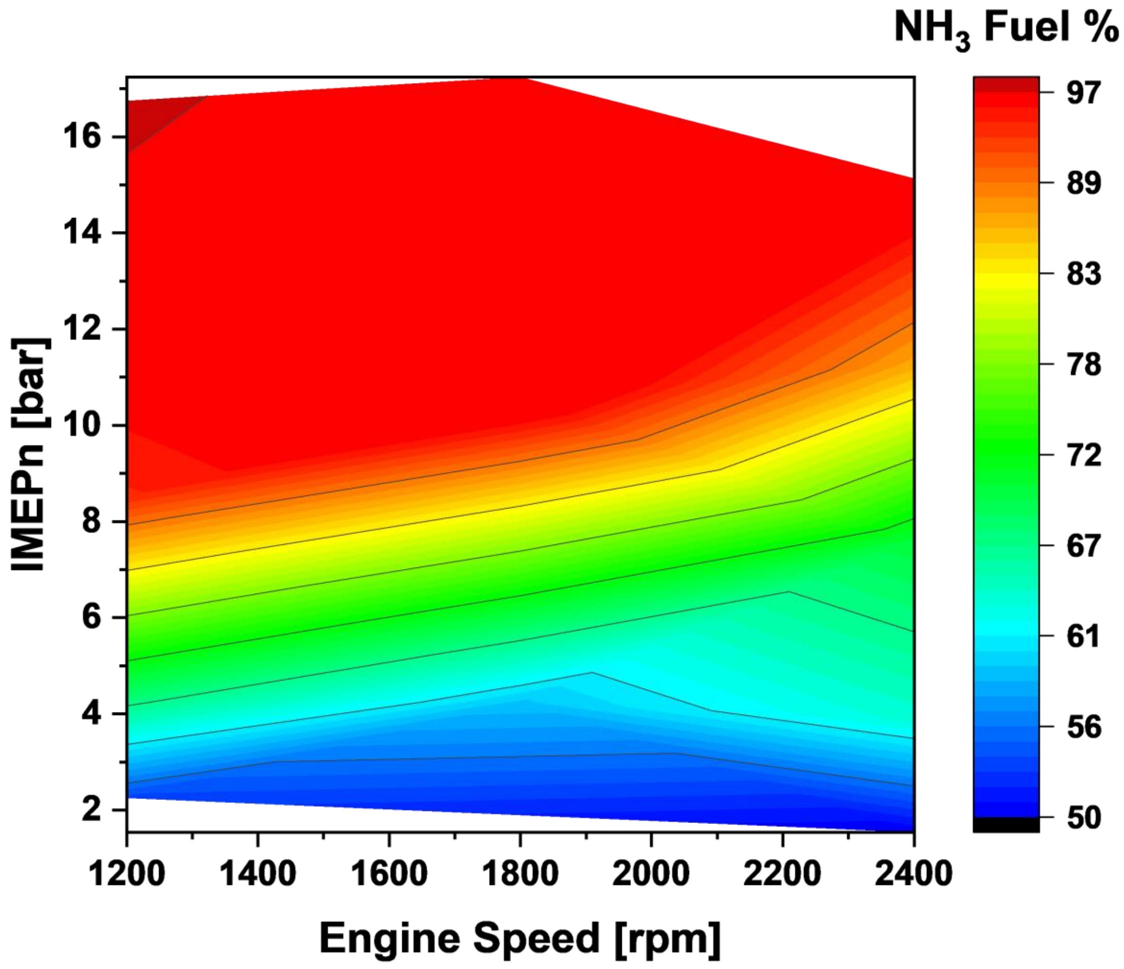
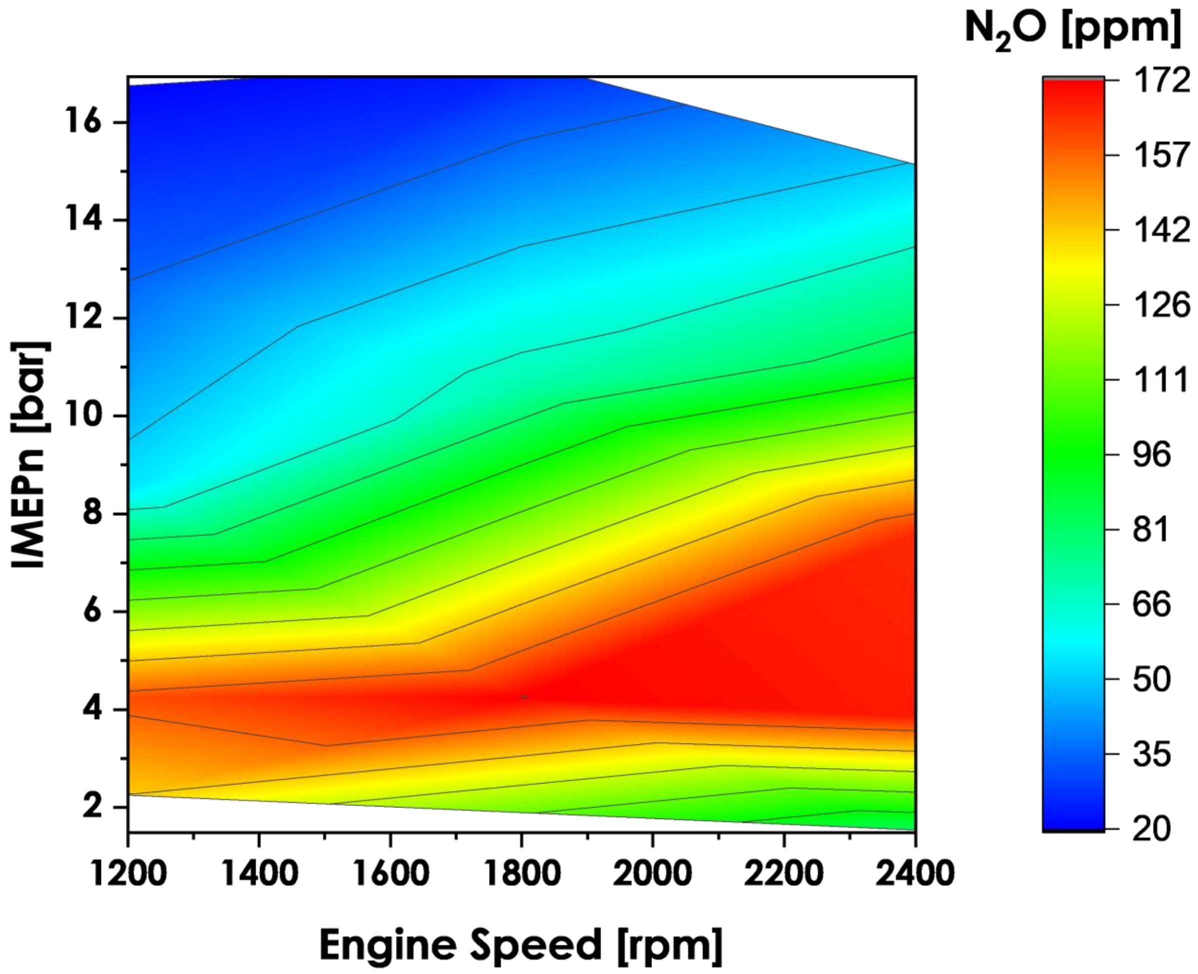
Dual fuel ammonia: High N_2O emissions at low loads where NH_3 combustion efficiency is low





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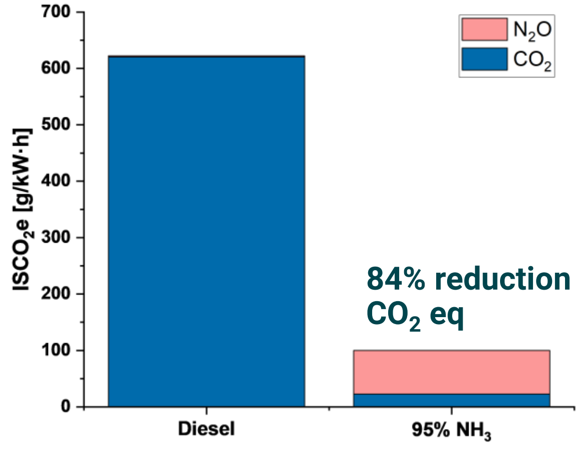

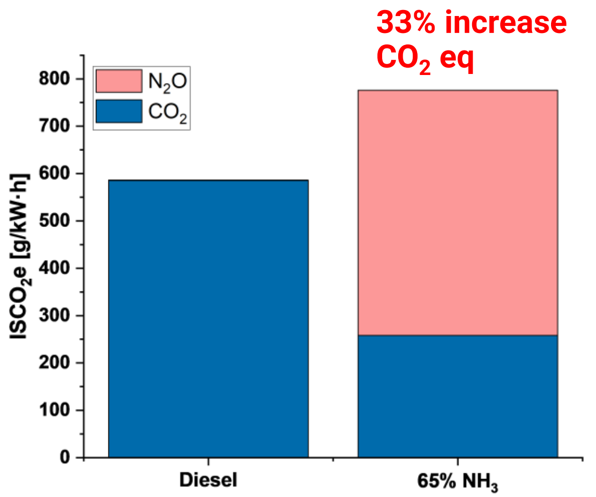

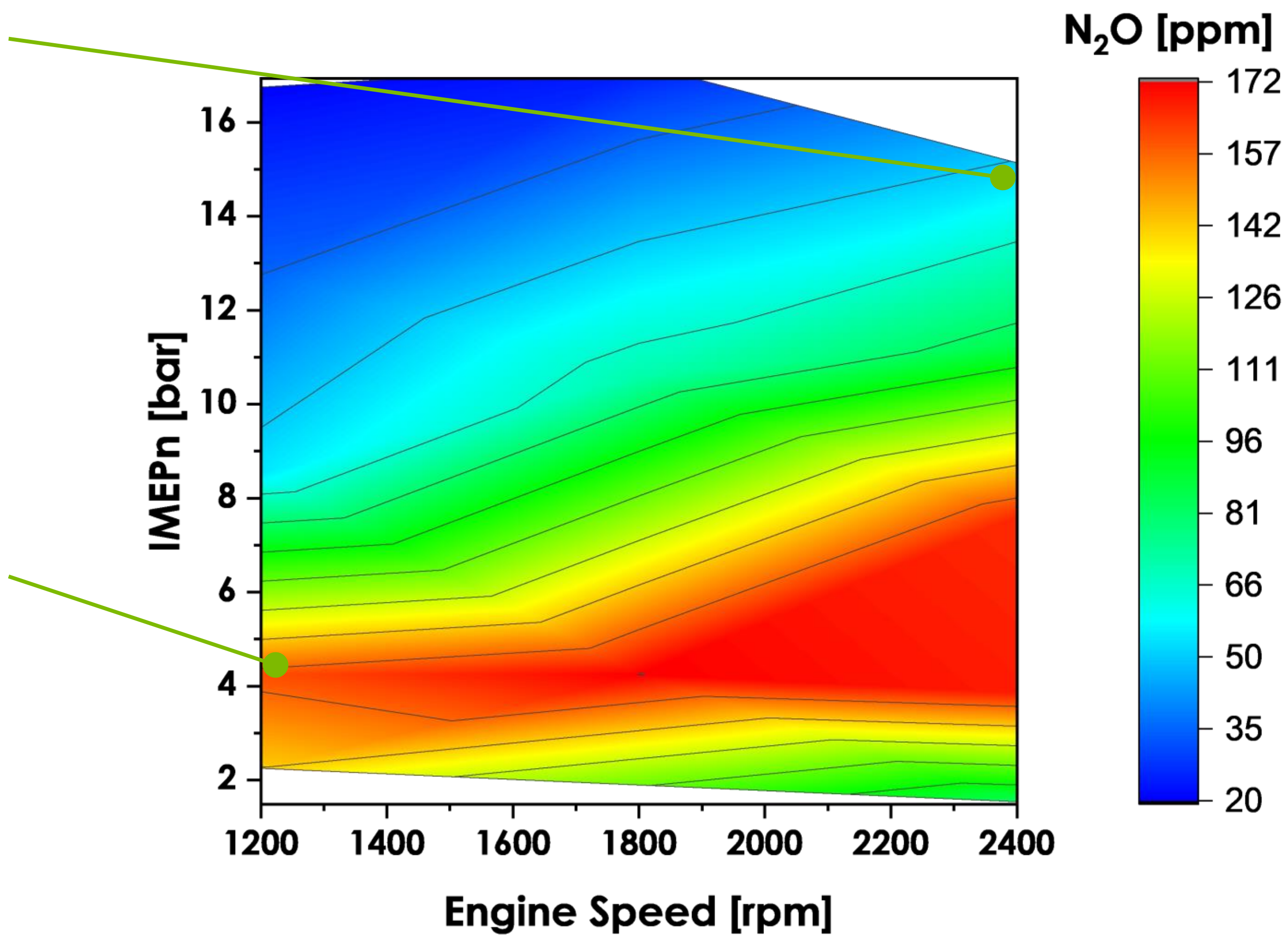

(N_2O = 273x more potent GHG than CO_2)

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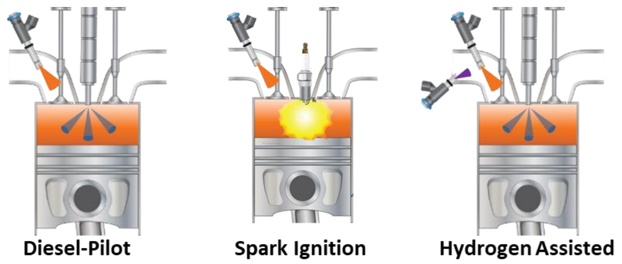
Dual fuel ammonia: High N_2O emissions at low loads where NH_3 combustion efficiency is low

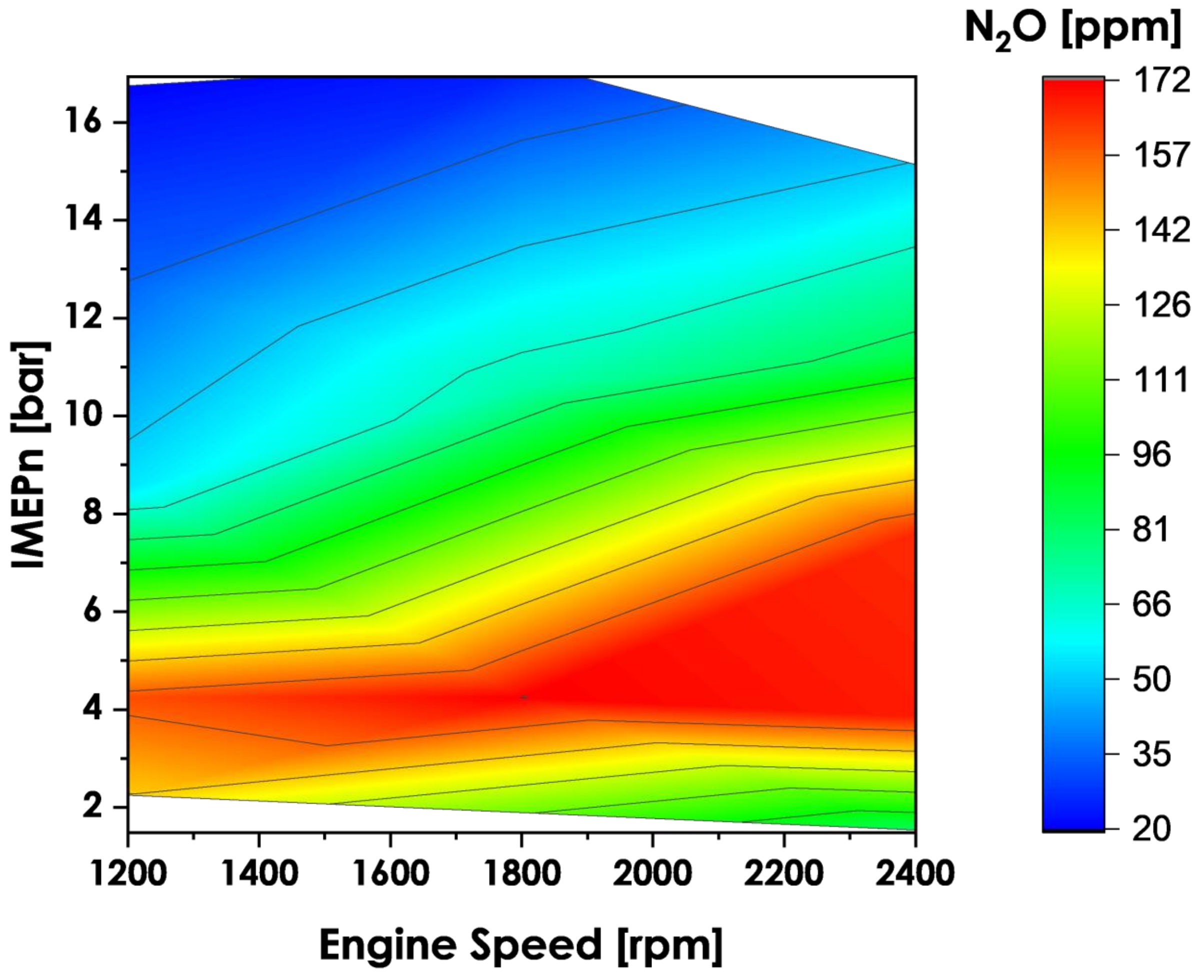
Combustion Strategy Development



Air-to-fuel ratio

Injection schedule

Modeling



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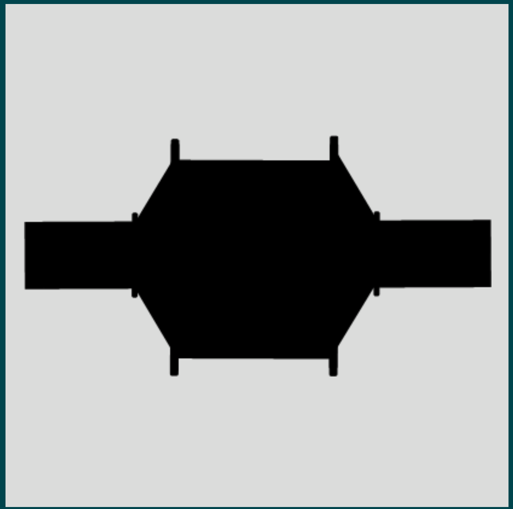
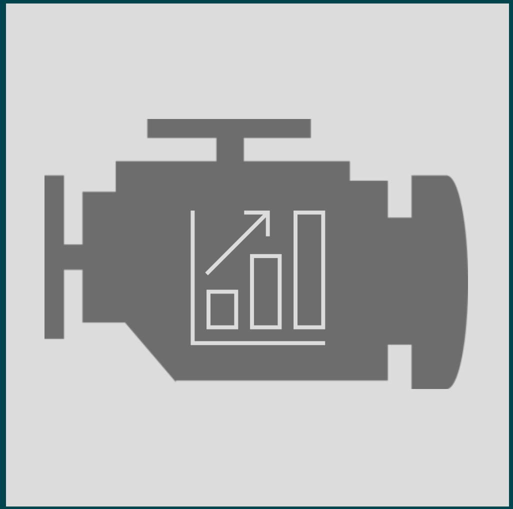
Engine Mapping



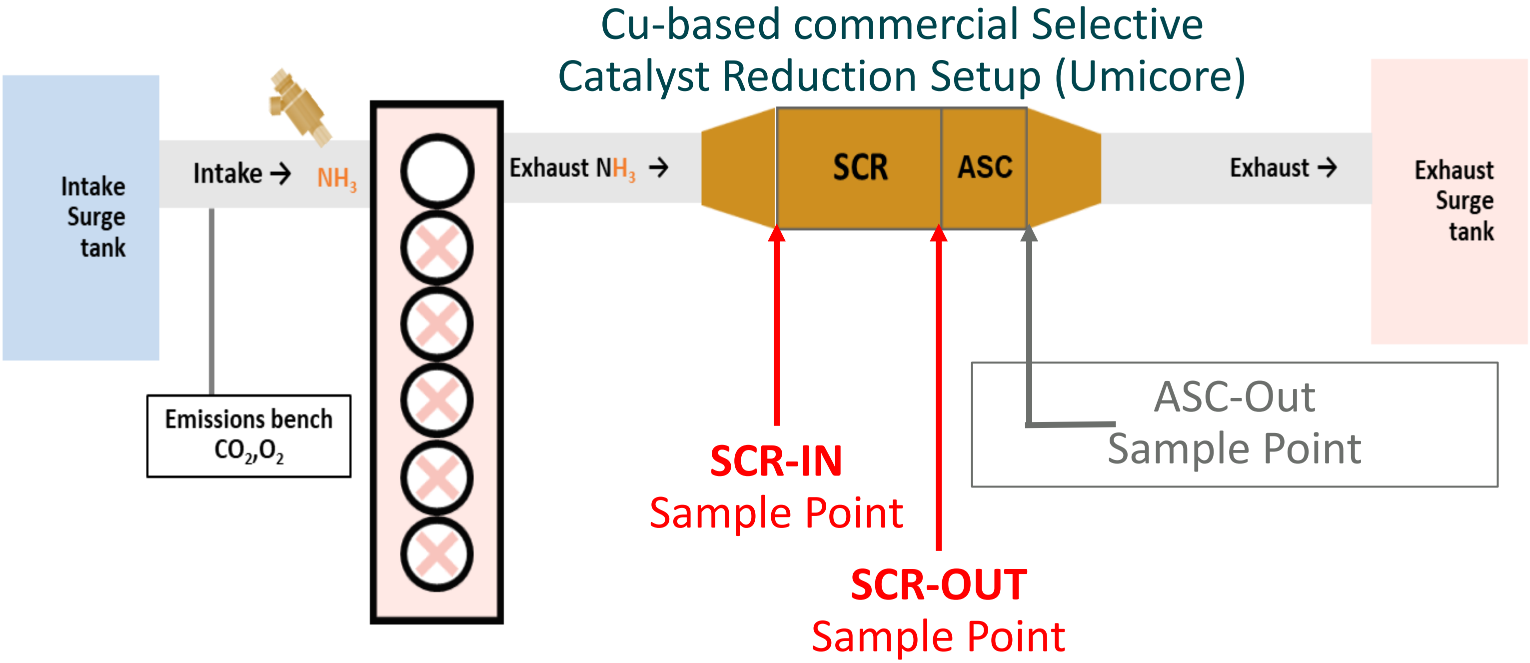
Aftertreatment & Emissions Impacts

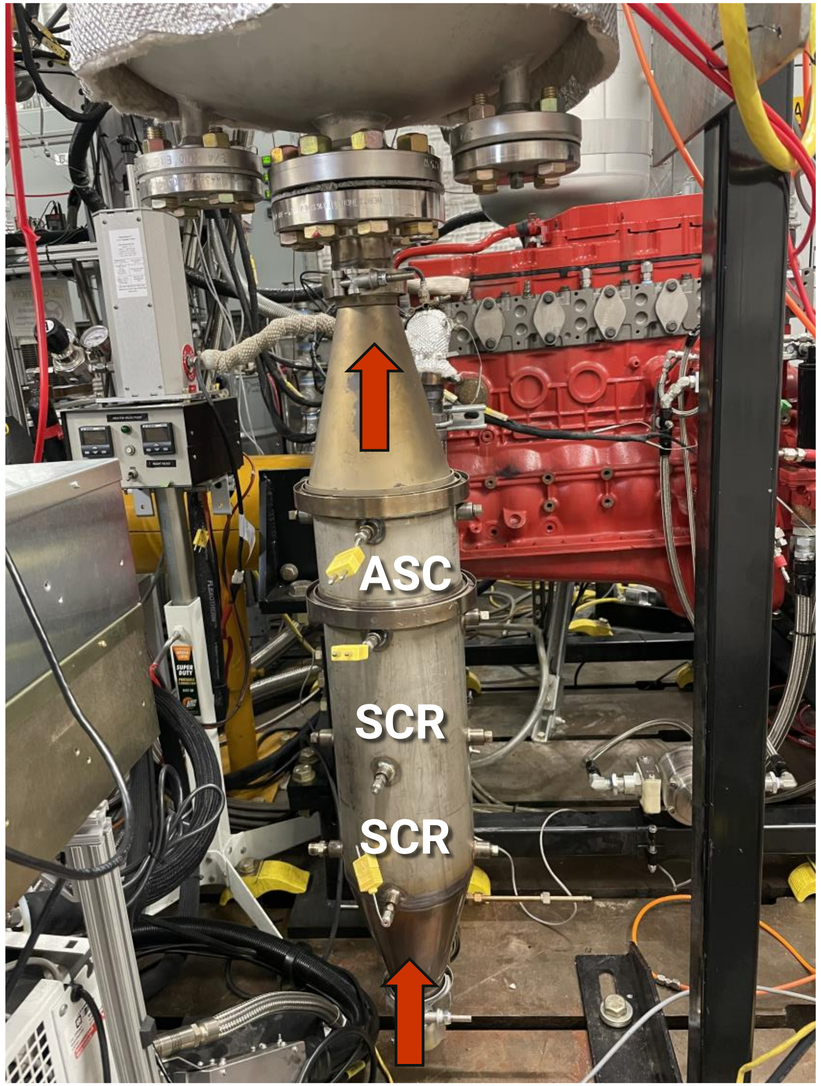


Thermodynamic Efficiency

Commercial SCR + ASC aftertreatment system has been installed

Initial focus is on SCR (highest relevance to existing marine engines)





Selective catalytic reduction uses ammonia to reduce NO_x

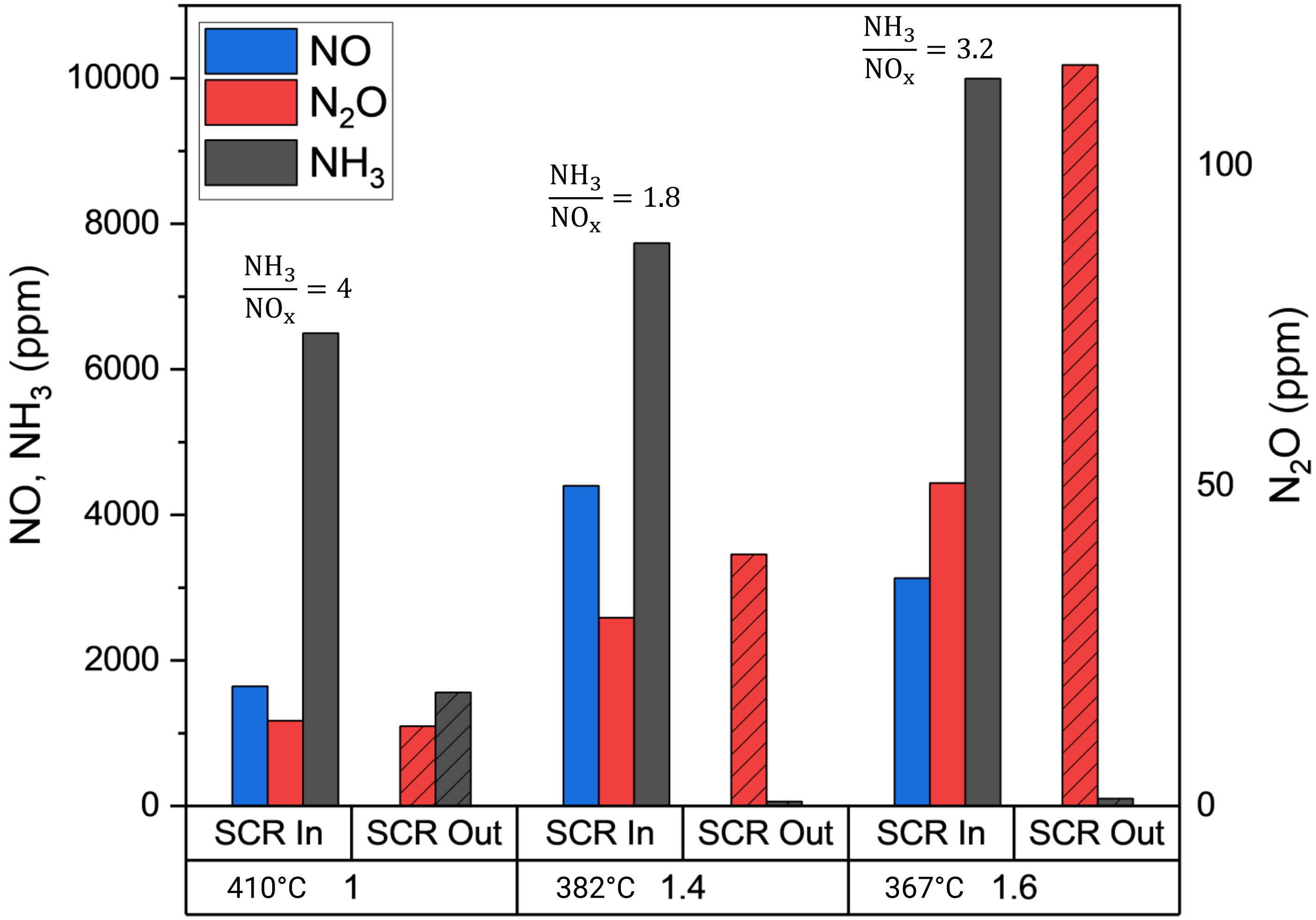
$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$ (Standard SCR Reaction)

$$\frac{\mathrm{NH_3}}{\mathrm{NO_x}} = 1 \text{ (Ideal stoichiometry)}$$

Competing NH_3 Oxidation Pathways

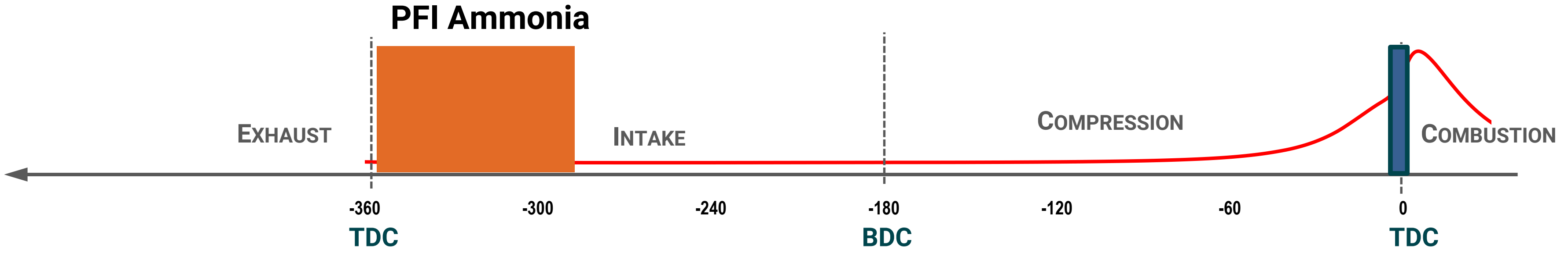
$2NH_3 + 2O_2 \rightarrow N_2O + 3H_2O$
$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$
$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

Initial SCR results show potential for NO_x, NH_3 abatement, depending on operating conditions. Optimization needed.

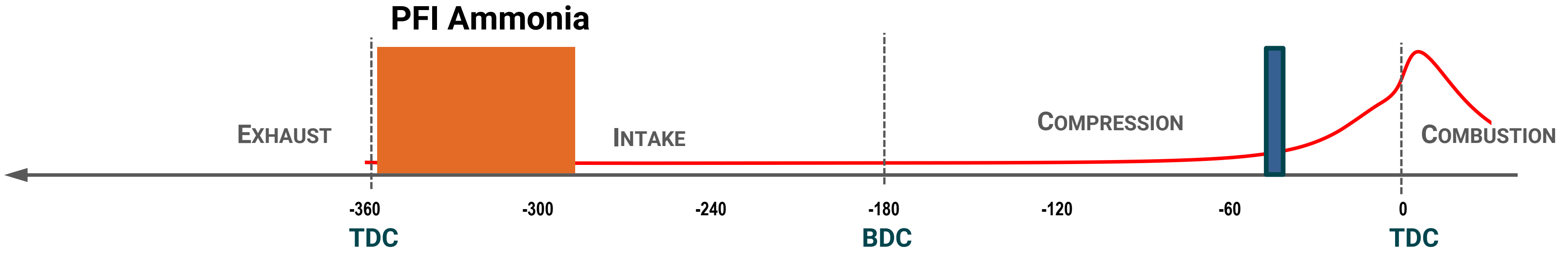


1200 rpm, ~12.6 bar IMEP

Ammonia dual-fuel direct injection strategies
Low-pressure dual-fuel engine (4-stroke) with direct injection pilot fuel



Conventional diesel timing (late pilot)



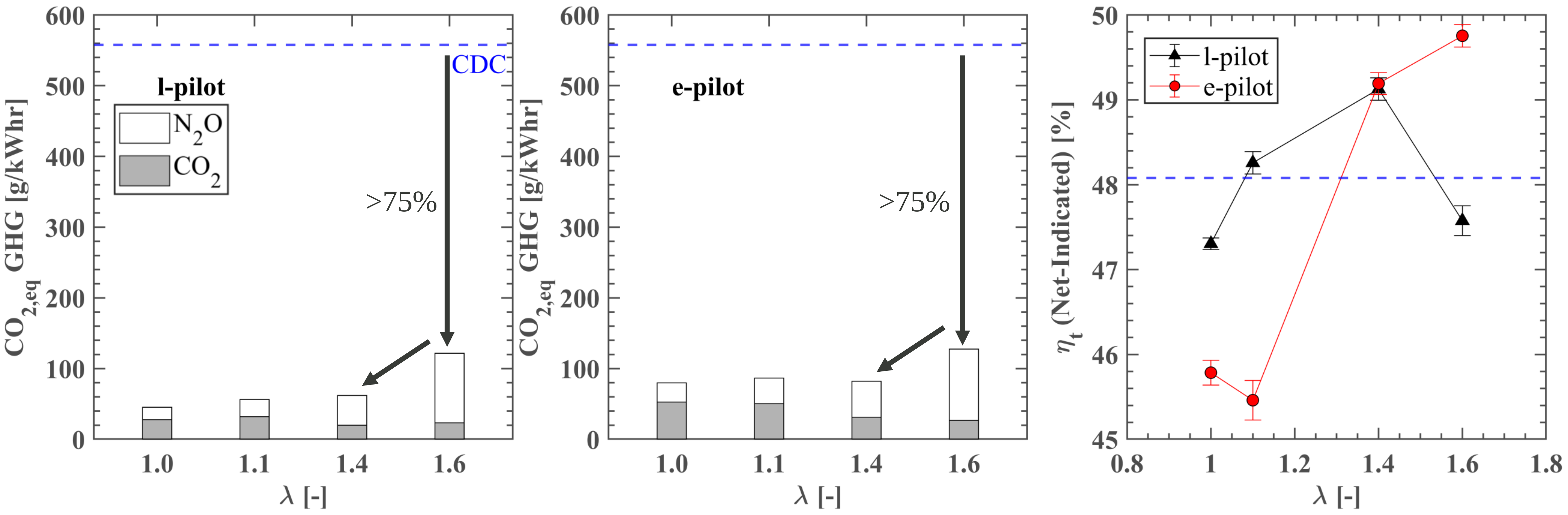
Early pilot

Ammonia Port Injection

Diesel Direct Injection

Diesel-like η_t and further reduction of N_2O possible with richer ℓ-pilot and e-pilot conditions

1200 rpm, ~12.6 bar IMEP



Note: Optimal (lowest engine-out N_2O) SOI case shown for a given λ

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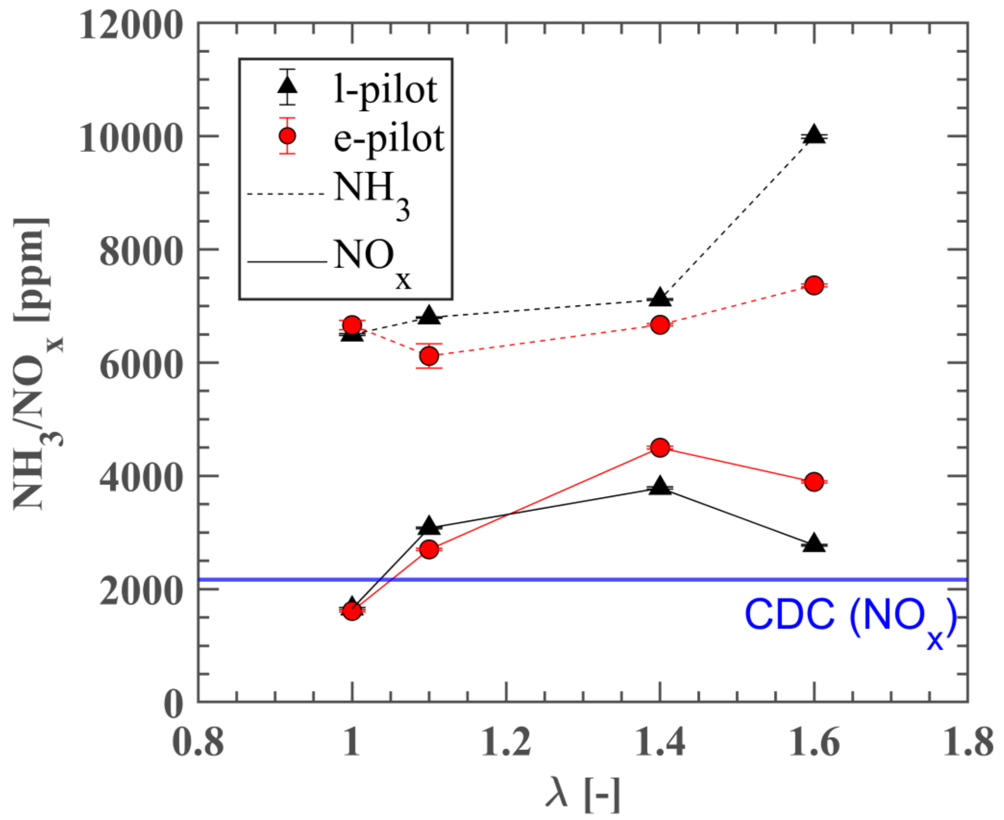
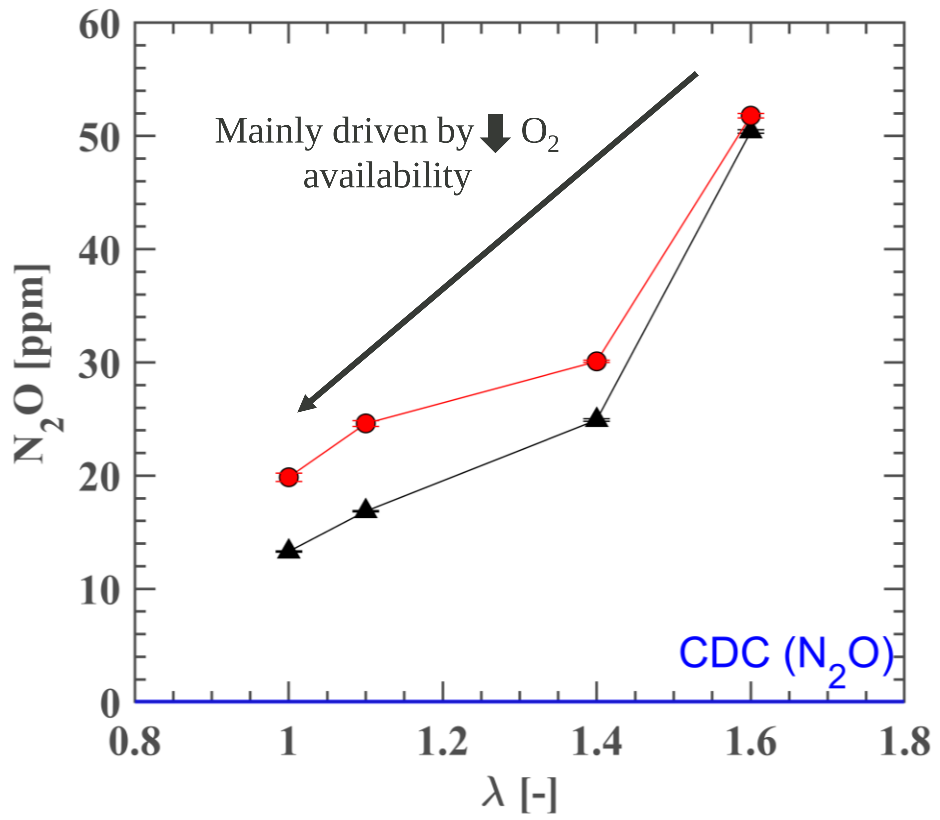
NO_x reduction without significant NH_3 slip over an SCR requires optimization; reduced N_2O formation at λ <1.6

1200 rpm, ~12.6 bar IMEP

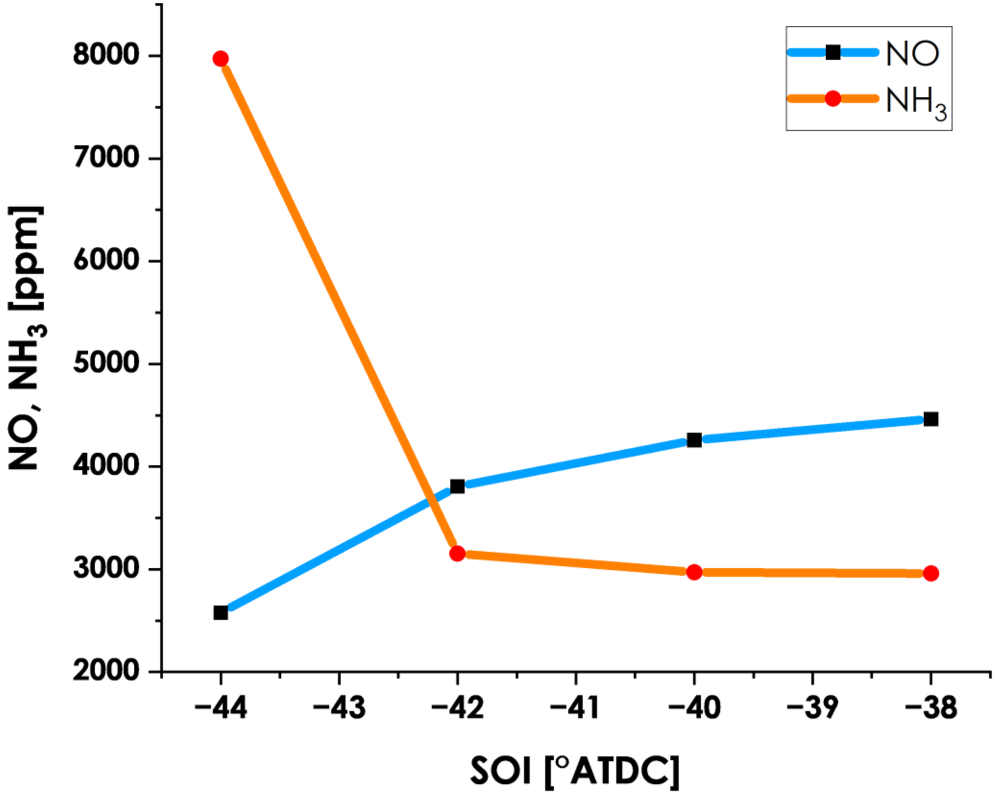




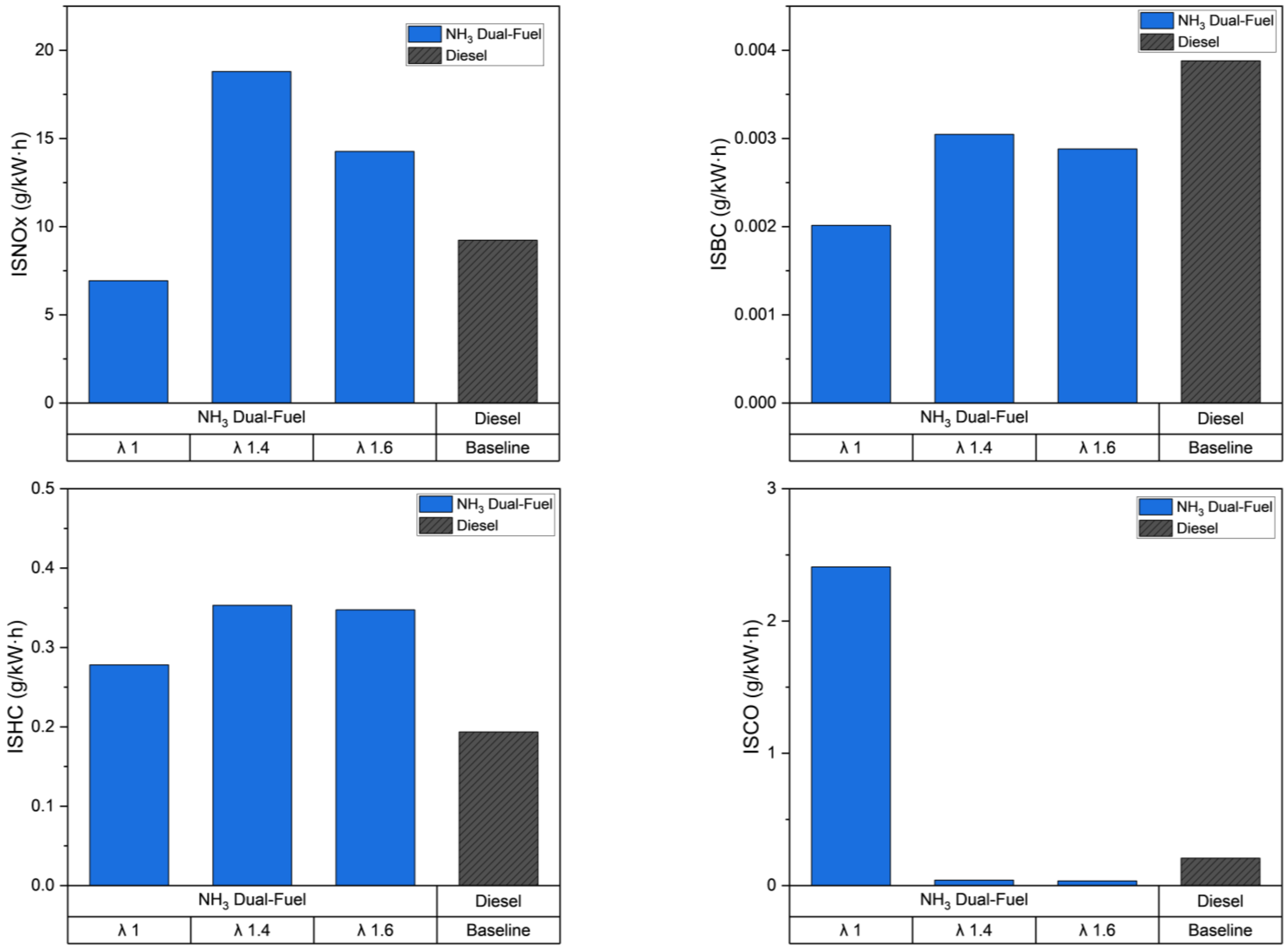
Note: Optimal (lowest engine-out N_2O) SOI case shown for a given λ

With early pilot strategy, optimization of the NH_3/NO ratio may be achieved at lower NH_3 substitution levels

1200 rpm, ~12.6 bar IMEP
83% NH_3 substitution, e-pilot



NH_3 dual-fuel combustion impacts engine-out criteria emissions: aftertreatment needed



1200 rpm, ~12.6 bar IMEP, > 90% NH_3 substitution, l-pilot

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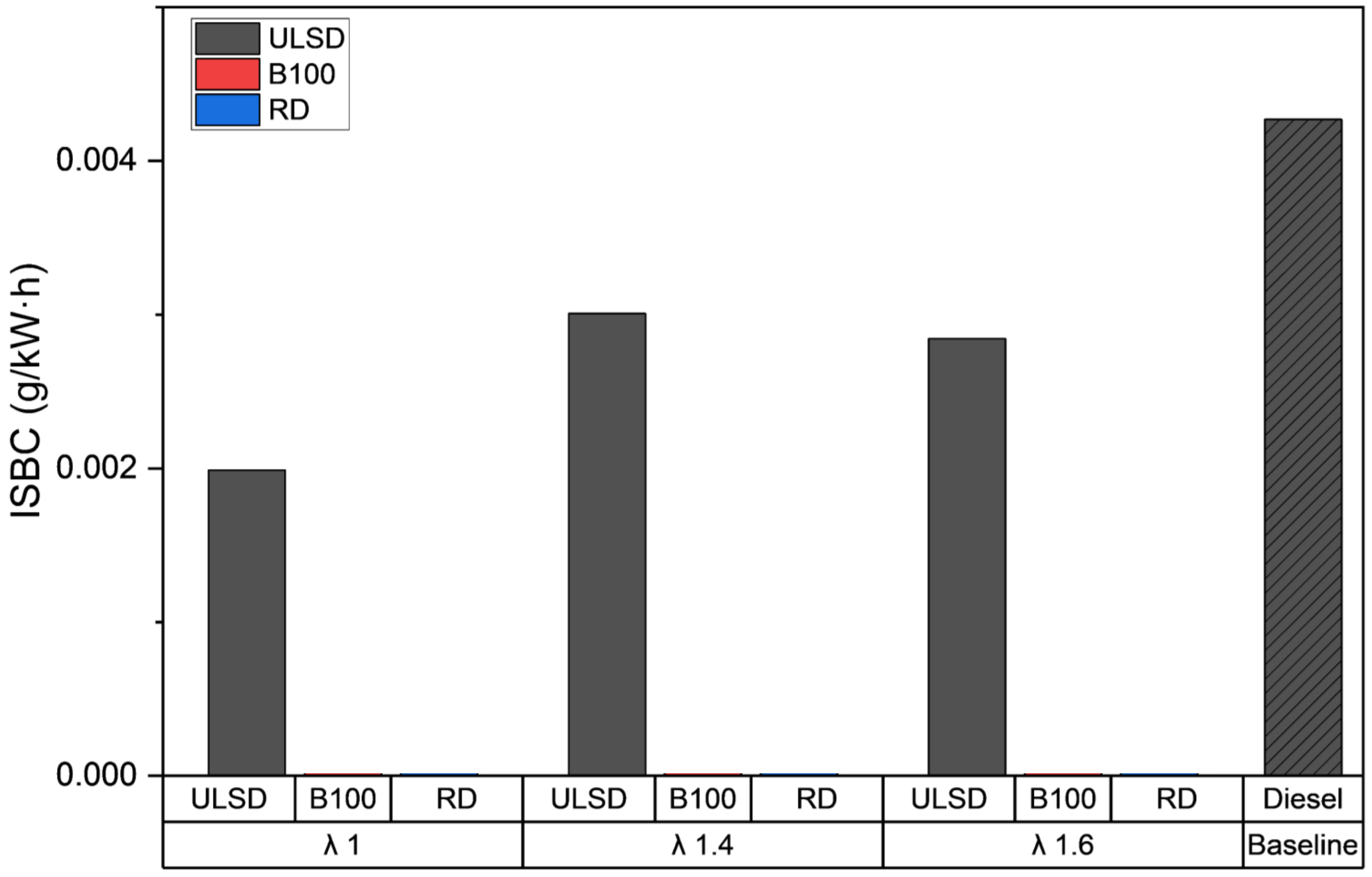
Soot reduction is far less than linear with diesel displacement



1200 rpm, ~12.6 bar IMEP, > 90% NH_3 substitution, I-pilot

Soot concentration measured with AVL Micro Soot Sensor (photoacoustic)

Further investigation needed to understand underlying reasons

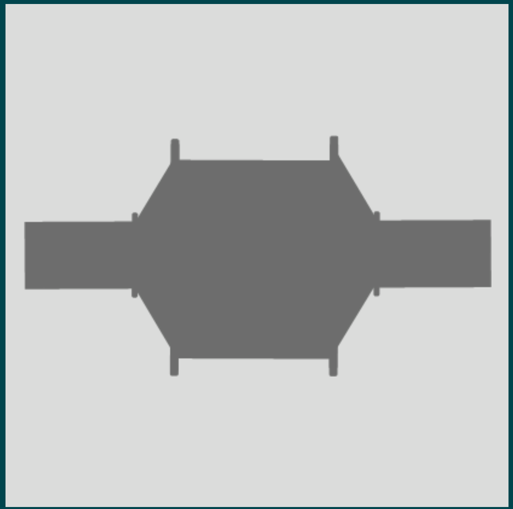
- Richer local conditions for diesel flame (increased HC emissions but reduced CO for lean NH_3 dual-fuel)
- Possible role of ammonium nitrate?

B100 (FAME) and RD (paraffinic) lack PAH found in ULSD

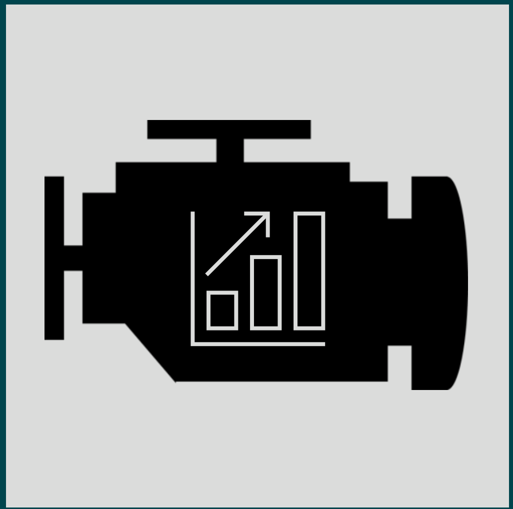
B100 also has 11% oxygen content

Fuel	*Cetane Number*	*Density [g/cc]*	*LHV [MJ/kg]*
NH_3	~ 0	0.609	18.8
ULSD	40.8	0.856	42.2
B100	54.1	0.884	37.3
RD	84.9	0.786	43.8

Engine Mapping

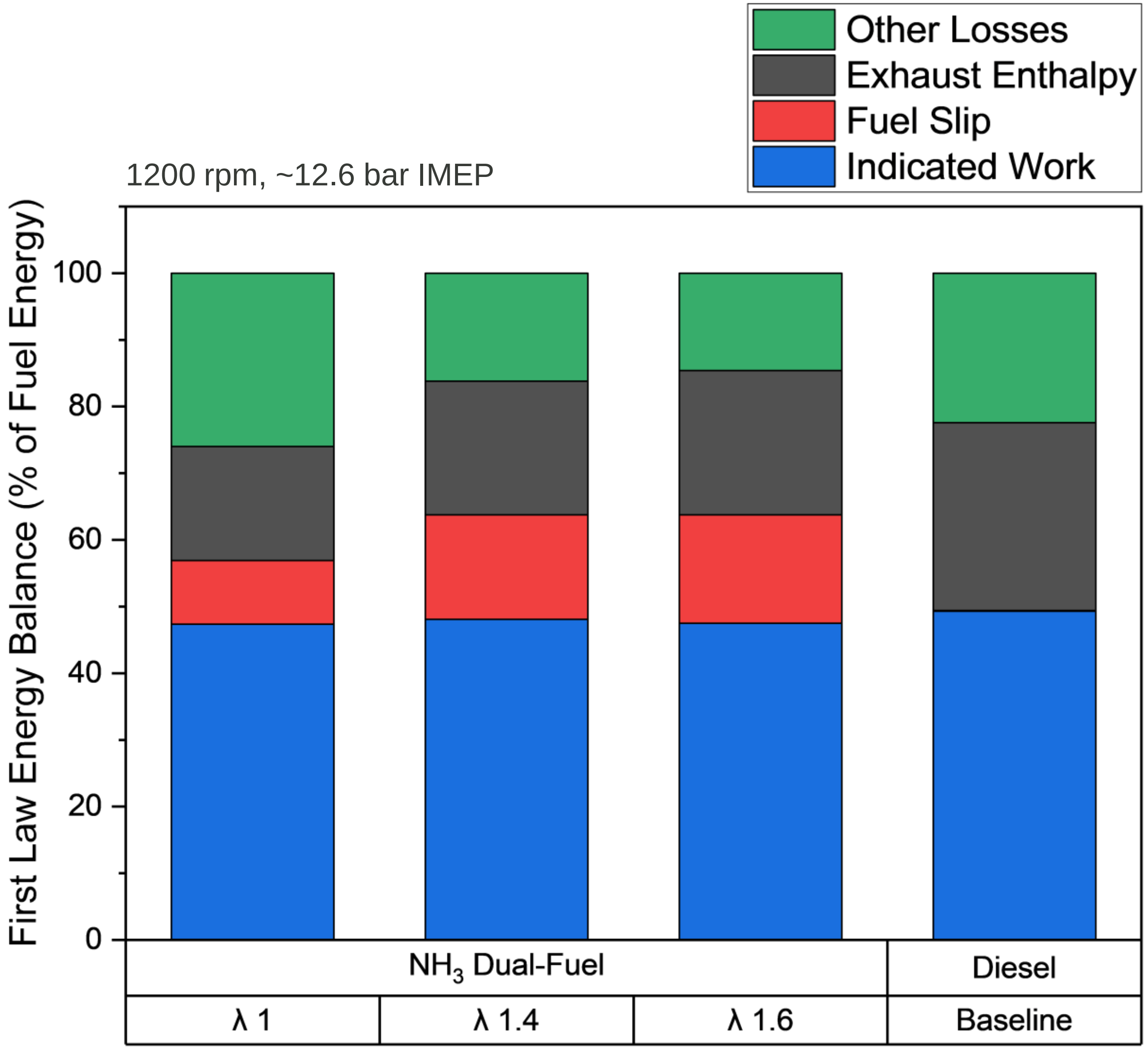


Aftertreatment & Emissions Impacts



Thermodynamic Efficiency

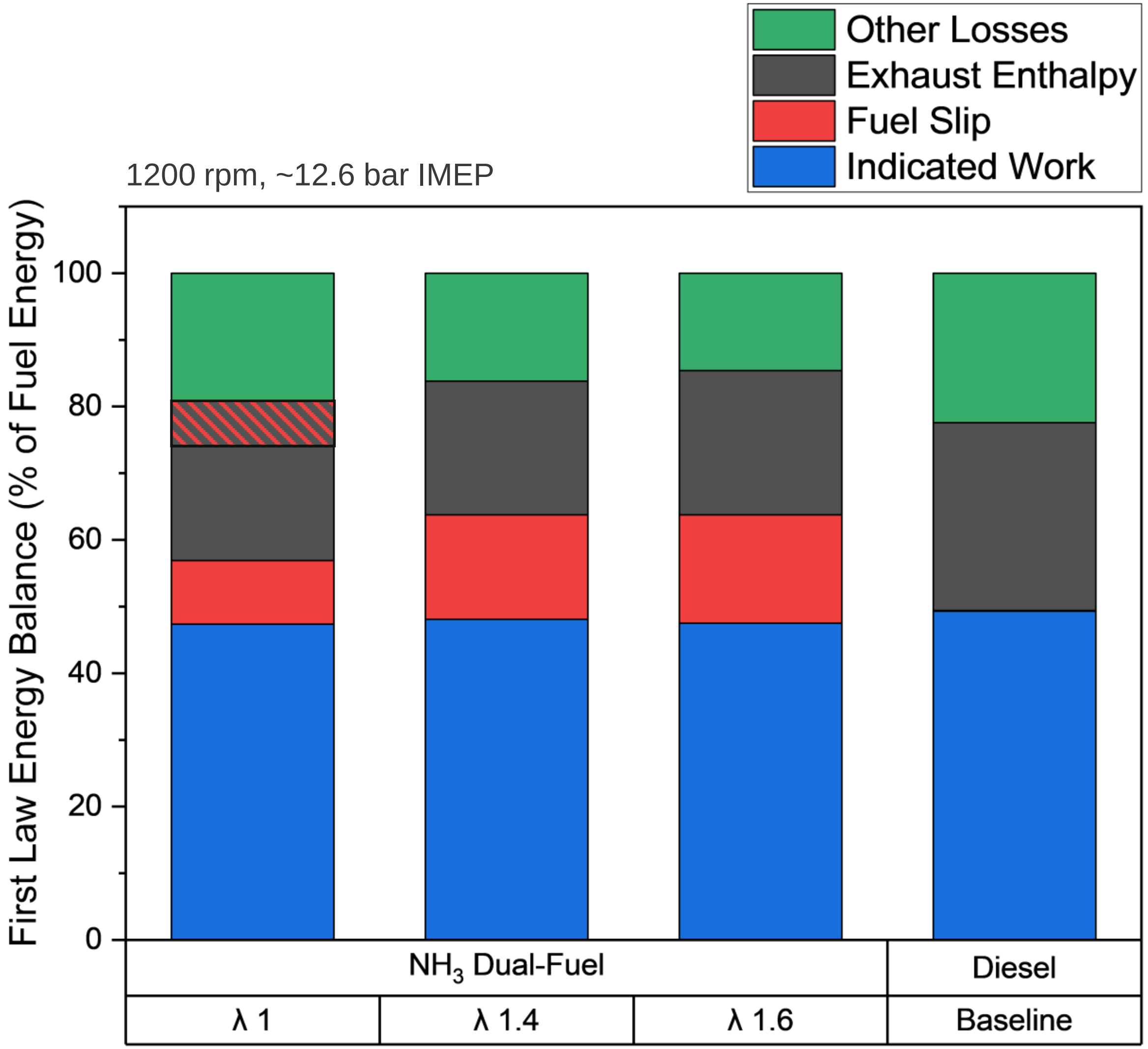
Engine efficiency for NH_3 dual-fuel is equivalent to diesel for dual-fuel NH_3 λ sweep with late pilot injection timings



Operating conditions

Engine speed	1200 rpm
Engine load	~ 12.6 bar IMEP
Ammonia energy substitution	90–96%
$P_{intake}-P_{exhaust}$	~ 15 kPa
λ	1, 1.4, 1.6
Diesel pilot SOI	*λ = 1: 9°BTDC* *λ = 1.4, 1.6: 3°BTDC*

Fuel slip (chemical energy of unburned NH_3 & HC) is significant (10–15% of fuel energy) for NH_3 dual-fuel operation



For lean cases, ~ 15% of fuel remains unburned

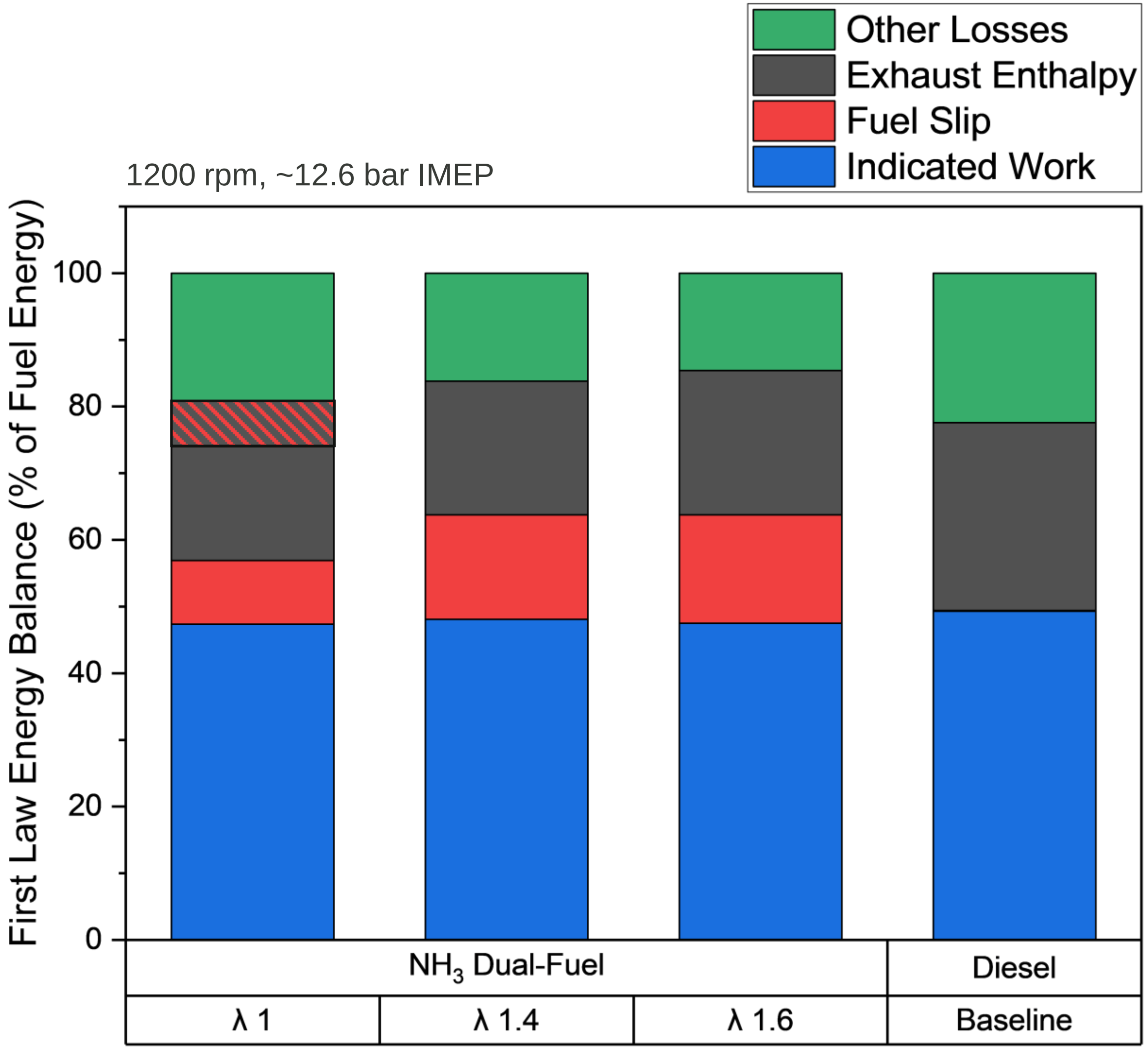
For stoich case, 10% of fuel unburned, but change not reflected in efficiency

Likely reforming some NH_3 to H_2

- H_2 not currently measured, so shows up as "Other"
- Quantity of H_2 needed to account for missing NH_3 slip is equivalent to H_2 that would be produced by cracking 4.9% of the NH_3 fuel

Implications for EGR operation

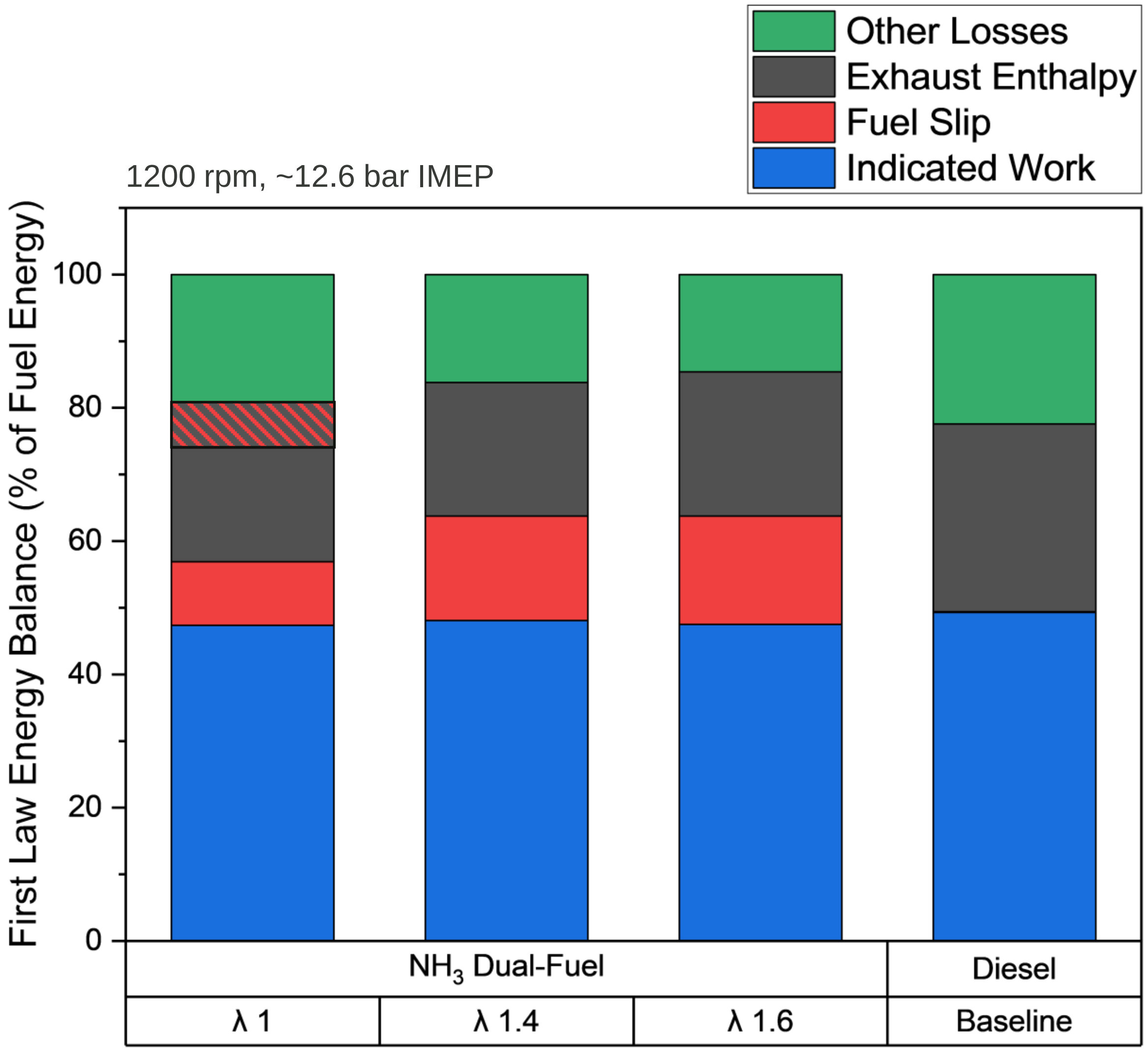
Other losses is the balance term and comprises heat transfer to coolant/oil/room as well as other unaccounted-for losses

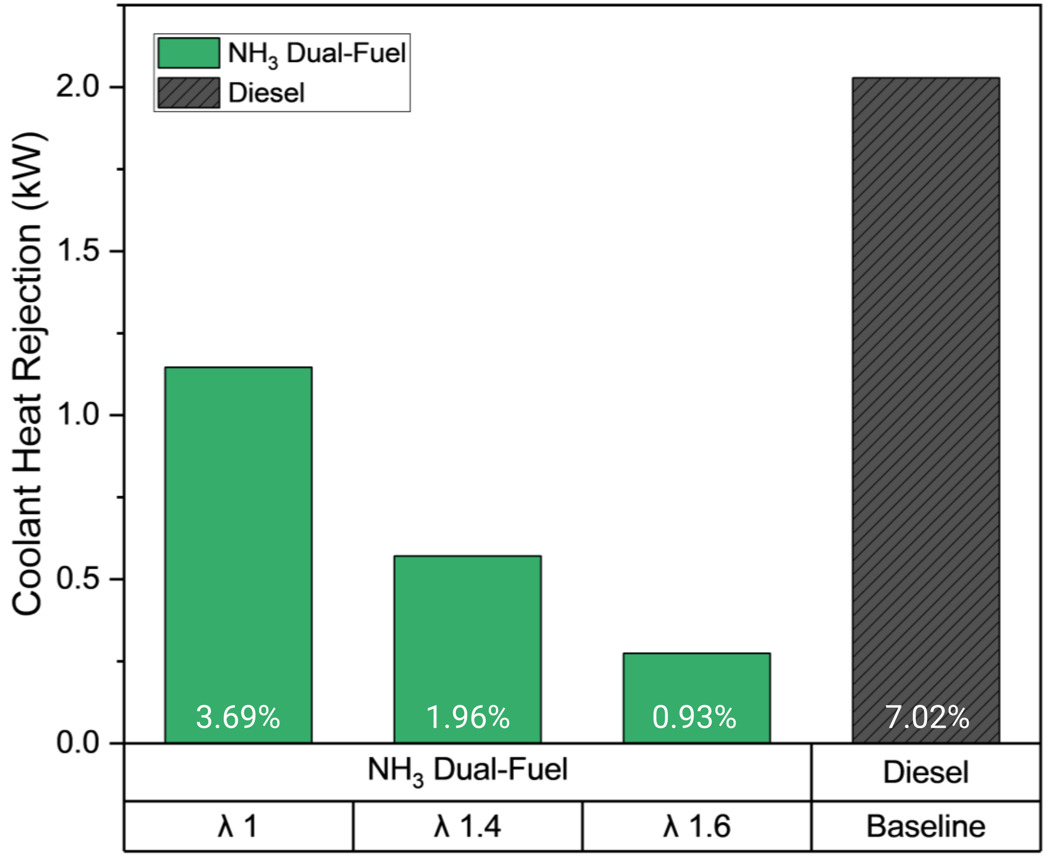


This is a full multi-cylinder engine converted to run on one cylinder

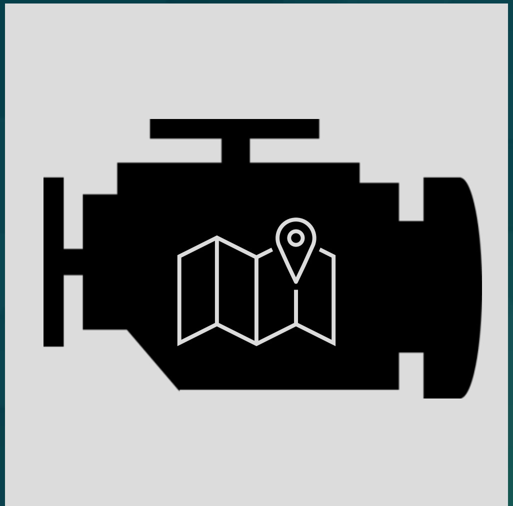
Convective heat transfer to the room, etc. is thus for the full block (balances of coolant vs oil HT, etc. may vary for full engine)

Heat transfer is significantly reduced for NH_3 dual-fuel operation relative to diesel



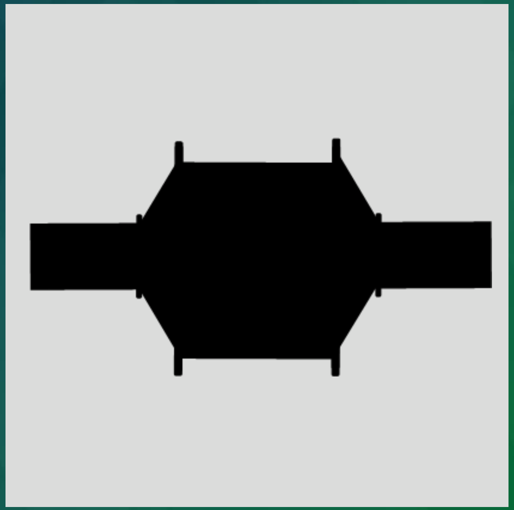


Questions?



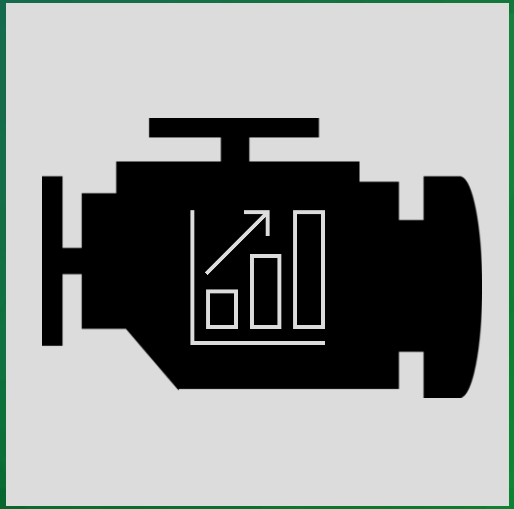
Dual-fuel approach effective for high NH_3 substitution

Combustion development needed at low loads



SCR shows potential for NH_3 + NO_x cleanup

N_2O formation is a concern



Thermal efficiency equivalent to diesel

Reduced heat transfer