

May 6, 2025

NH₃ Dual-Fuel Combustion Emissions in a 4-stroke Marine Diesel Engine

Ammonia Combustion Technology Group Meeting

Brian Kaul, Daanish Tyrewala, Scott
Curran, and Vitaly Prikhodko

Oak Ridge National Laboratory



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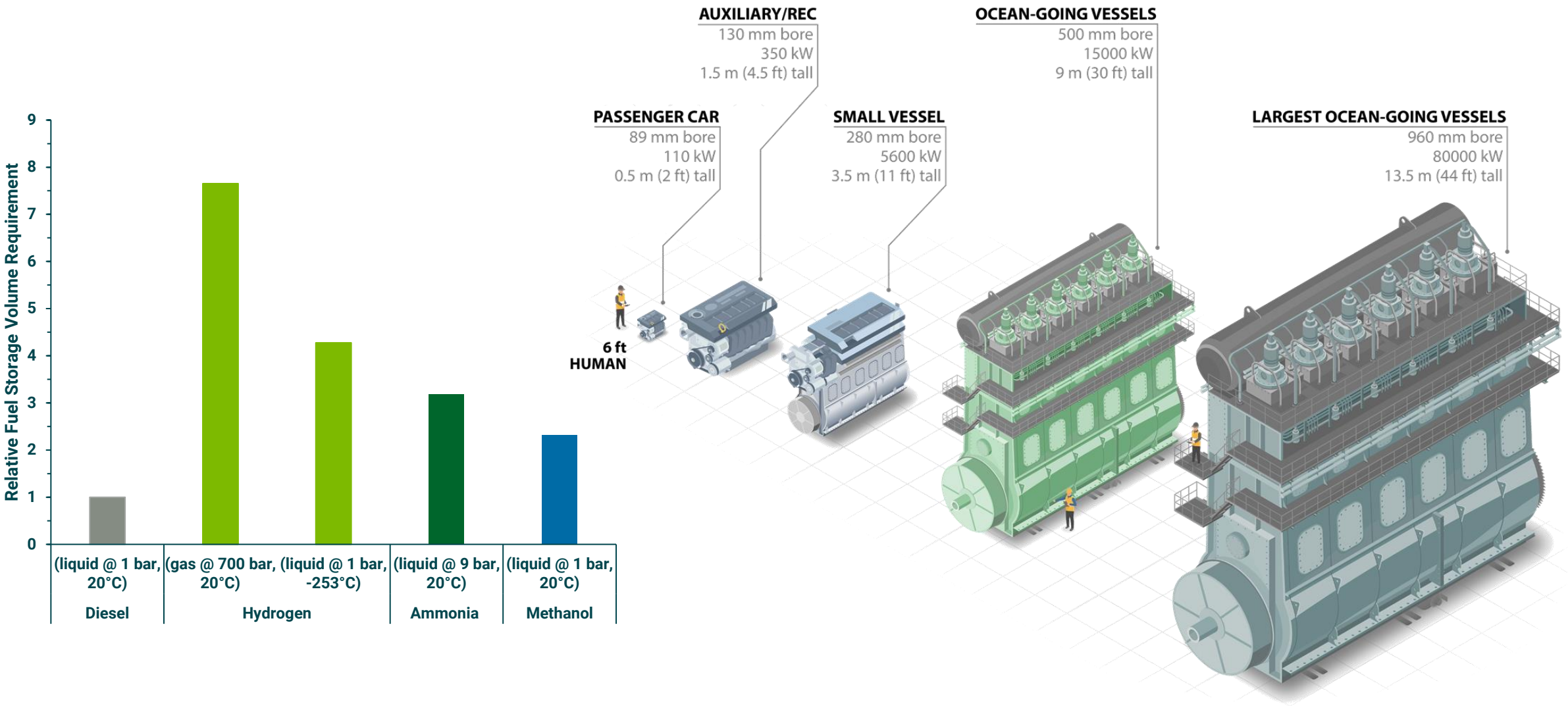


Acknowledgements

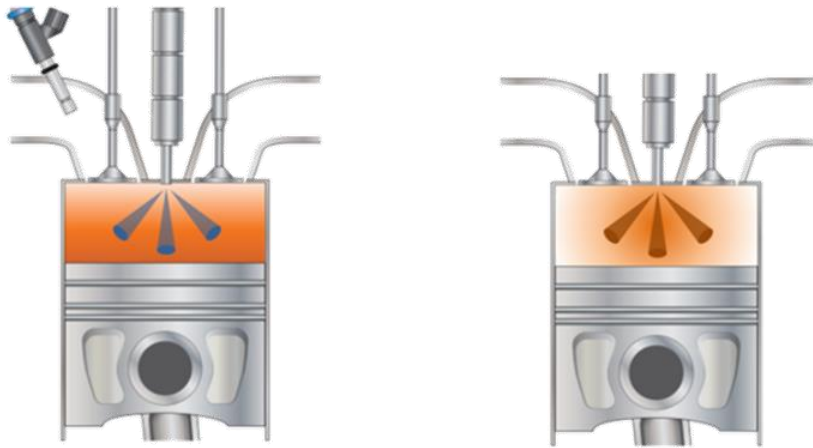
	DOE VTO Program Managers: Kevin Stork and Gurpreet Singh
	DOT MARAD Program Managers: Galen Hon, Will Nabach
	Co-investigators: Daanish Tyrewala, Scott Curran, Vitaly Prikhodko Support from: Gurneesh Jatana, Derek Splitter, Jonathan Willocks, Scott Palko, Steve Whitted, Jim Szybist, and Scott Sluder [+ Martin Wissink, Chloé Lerin, and Jordan Easter formerly of ORNL]
	Tim Lutz, David Langenderfer, and team at Cummins for providing engine platform, project guidance, and technical support for ISB/ISB-G
	Geoff Scott, Joe Spakowski, and team at Phinia for providing ammonia compatibility testing injectors and technical support
	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



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 CO₂ emissions reduction targets

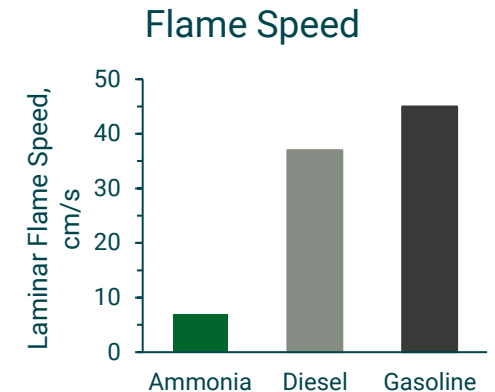
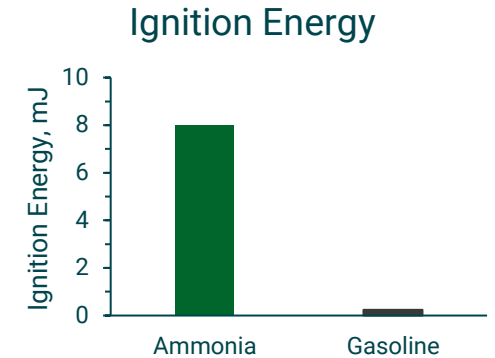
Ammonia has some challenges as an internal combustion engine fuel

- 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 operation¹

- 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

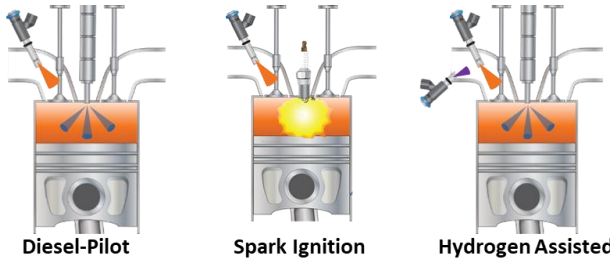
- Emissions control questions
 - Engine-out and aftertreatment-derived N₂O emissions
 - High engine-out NO_x and NH₃ emissions

- 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



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

Combustion Strategies

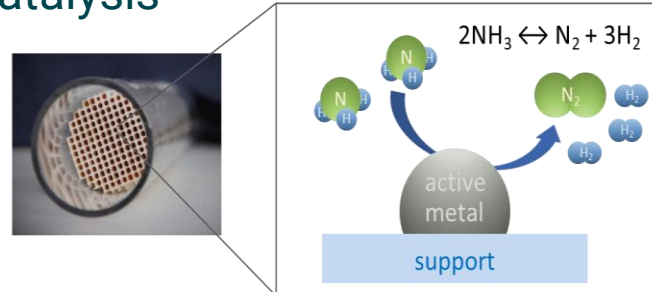


Cummins ISB
6.7L engine



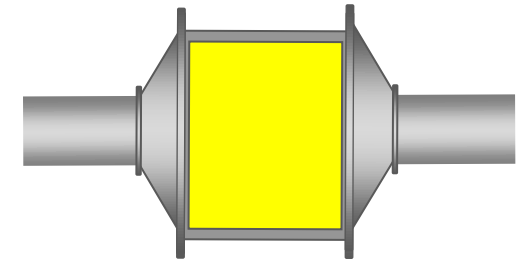
Ammonia
PFI injectors

$\text{NH}_3 \rightarrow \text{H}_2$ Decomposition Catalysis



Synthetic gas flow reactors

Emissions Controls



Experimental aftertreatment system

SCR: selective catalytic reduction
ASC: ammonia slip catalyst

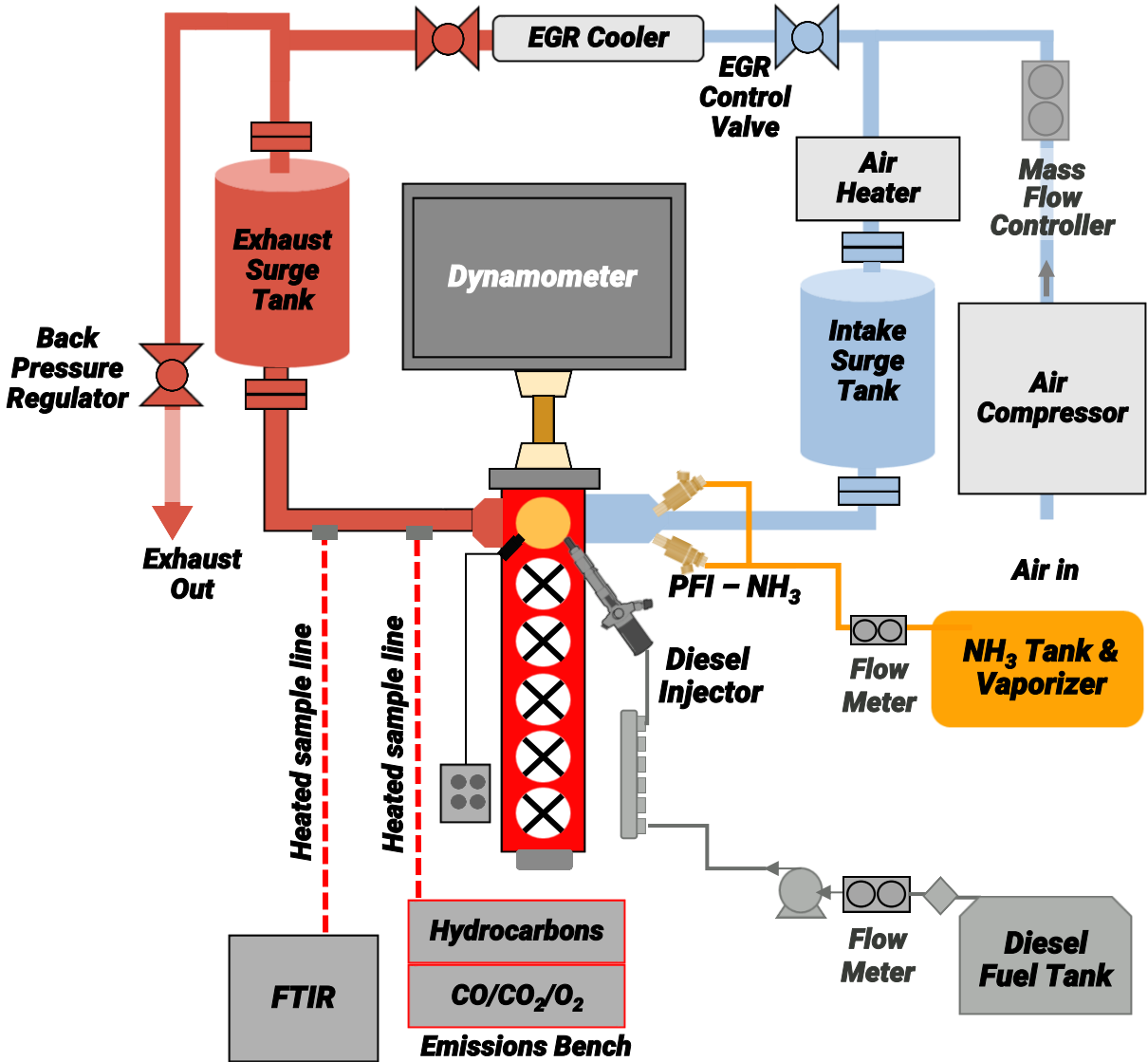
Developing model validation data at a small scale that can be applied to all scales of engines

Ammonia dual-fuel experiments were conducted on a single-cylinder Cummins ISB with PFI NH₃ + DI pilot fuel

Engine Specifications

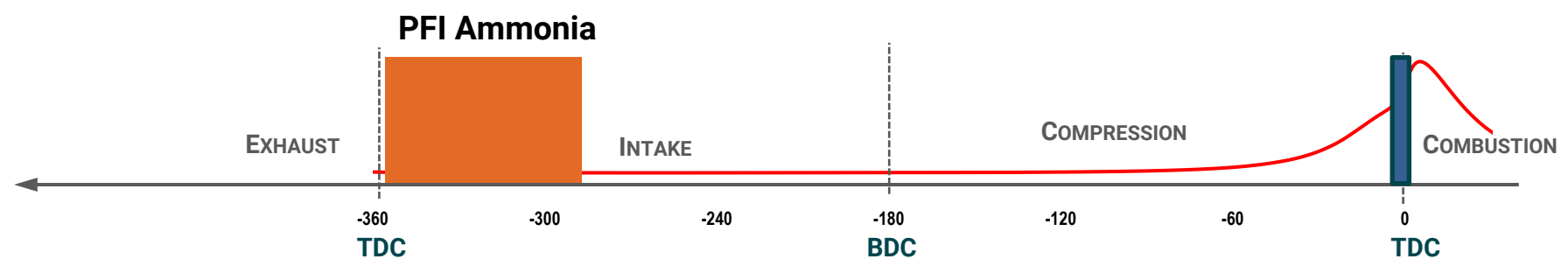
Bore x stroke	107 x 124 mm
Connecting rod length	192 mm
Displacement (1 cyl)	1.12 L
Compression ratio	20:1
Direct injection fuel supply	On-engine high-pressure common-rail pump
Port injection fuel supply	NH ₃ cylinder/vaporizer

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

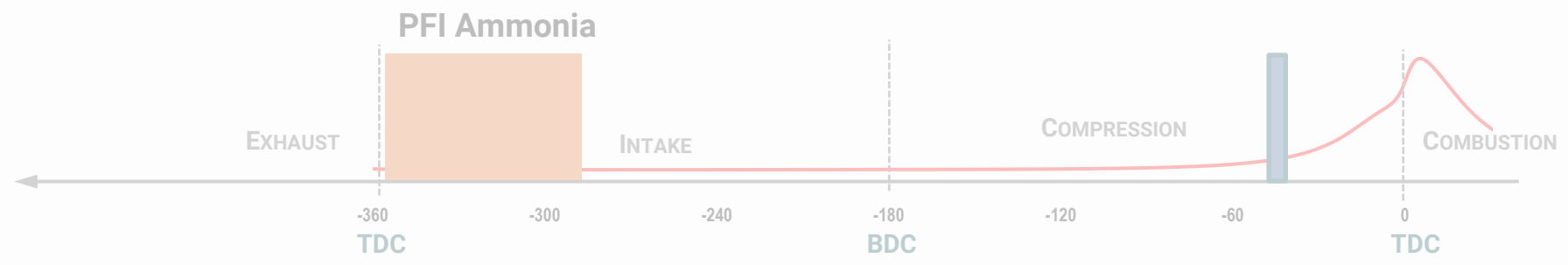


Ammonia dual-fuel direct injection strategies

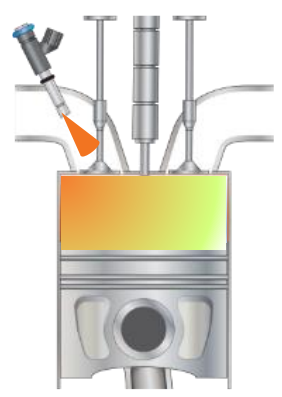
Low-pressure dual-fuel engine (4-stroke) with direct injection pilot fuel



Conventional diesel timing (late pilot)



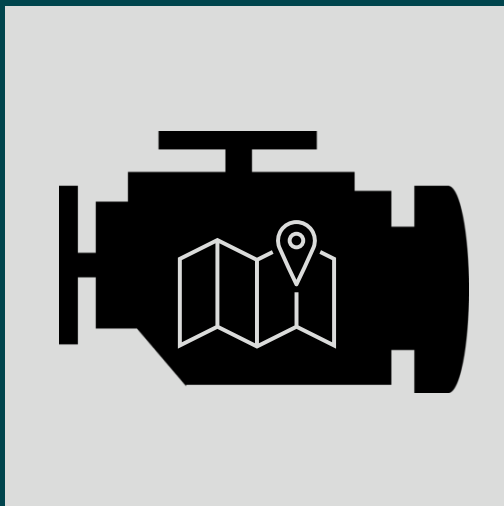
Early pilot



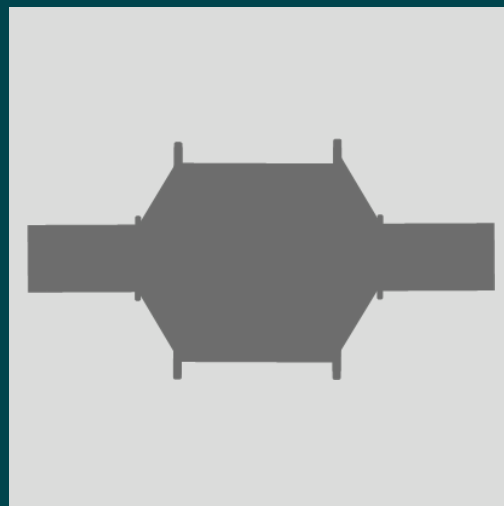
Ammonia Port Injection



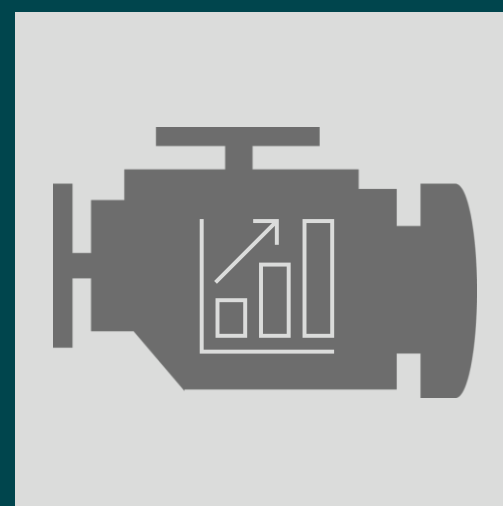
Diesel Direct Injection



Engine Mapping

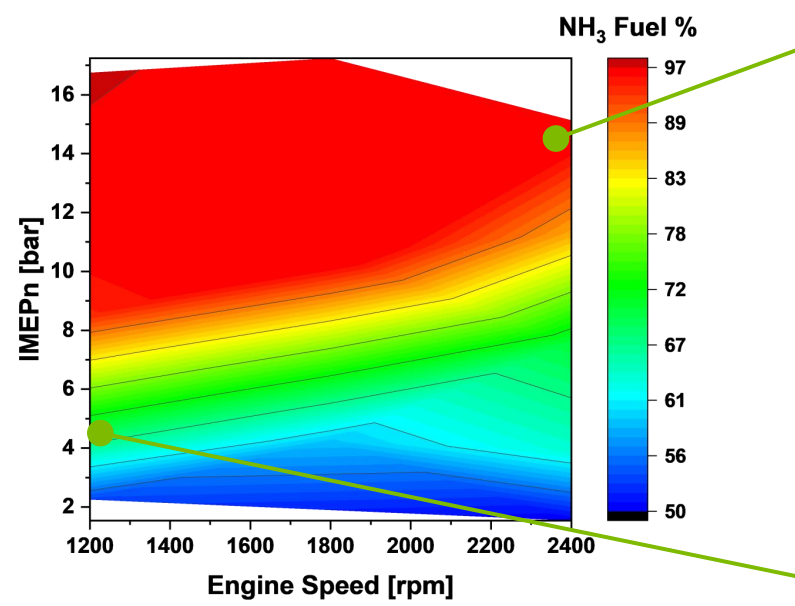


**Aftertreatment &
Emissions Impacts**

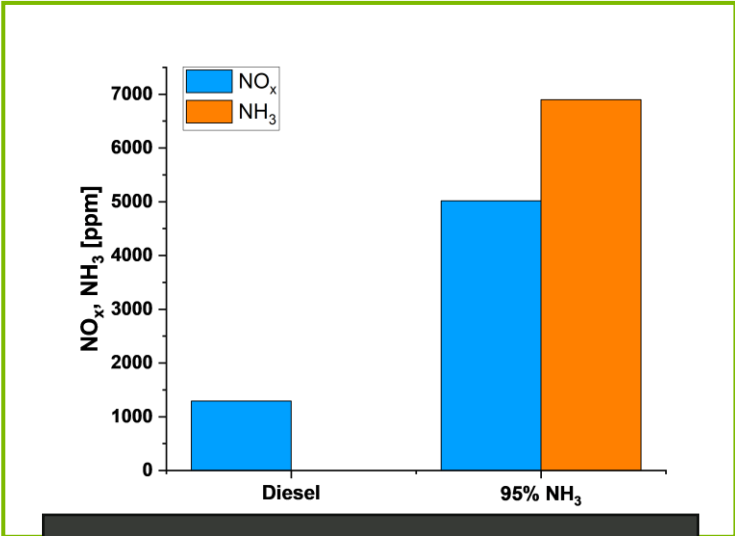


**Thermodynamic
Efficiency**

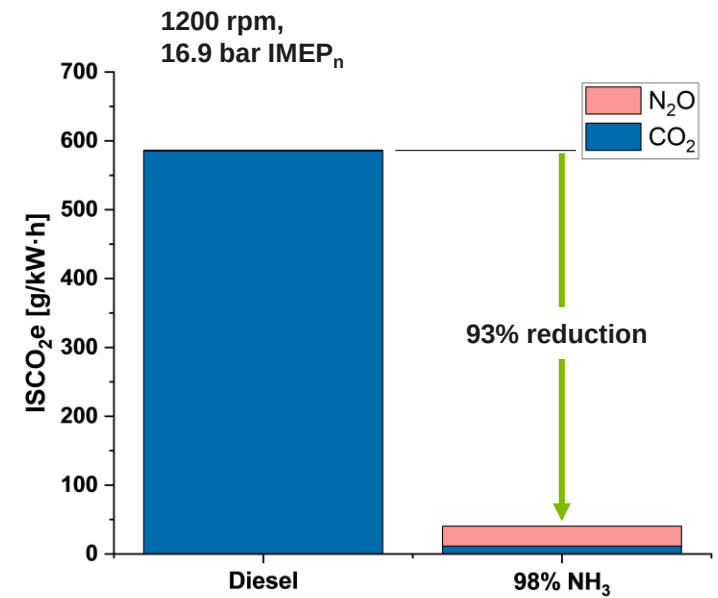
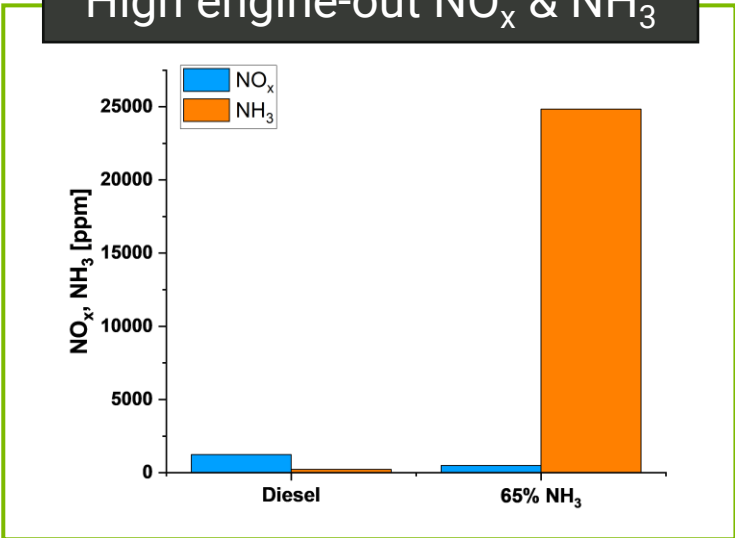
Mapping experiments for dual-fuel NH_3 provide insights into opportunities and challenges for NH_3 combustion in 4-stroke engines



95–98% NH_3 substitution demonstrated at full load

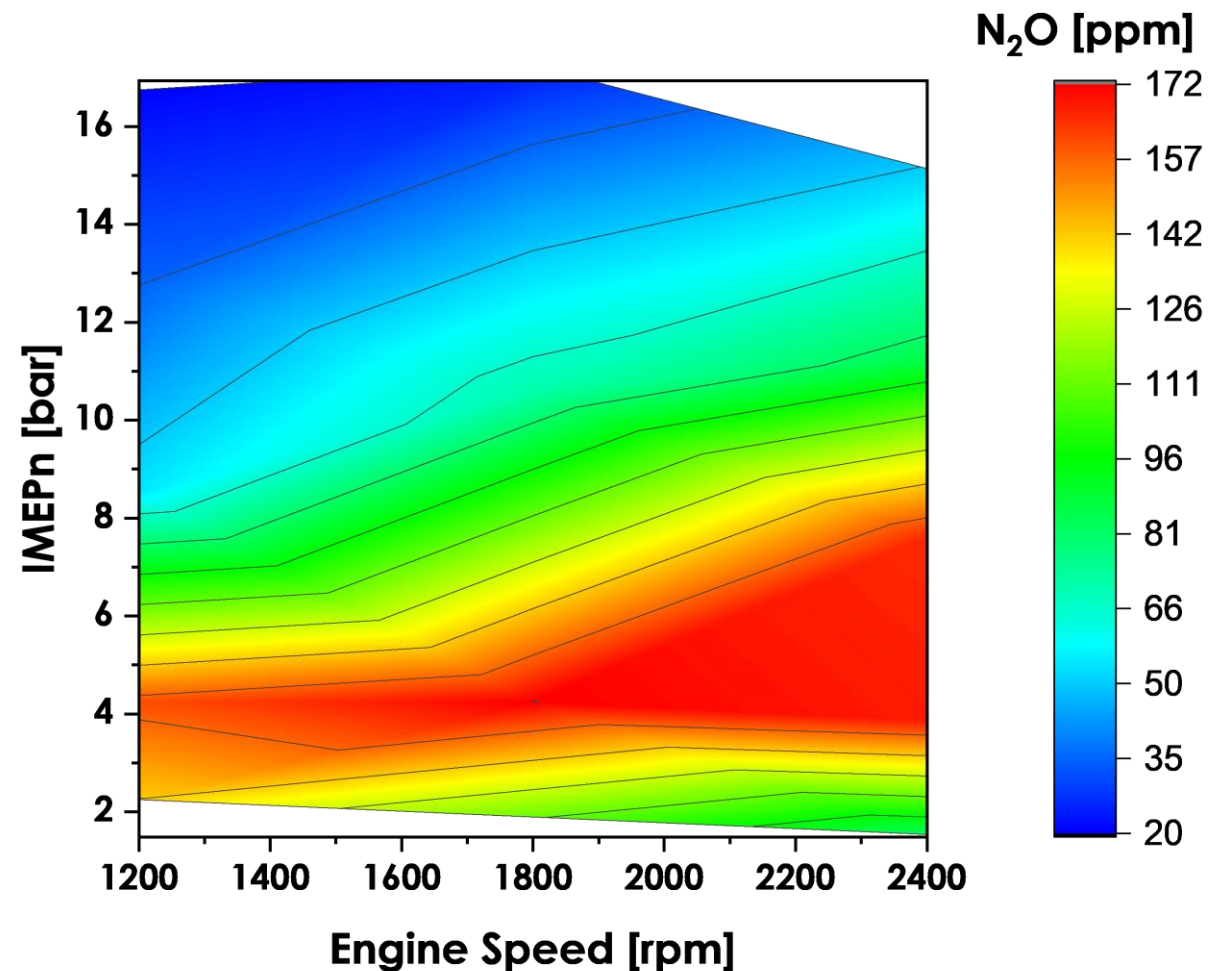
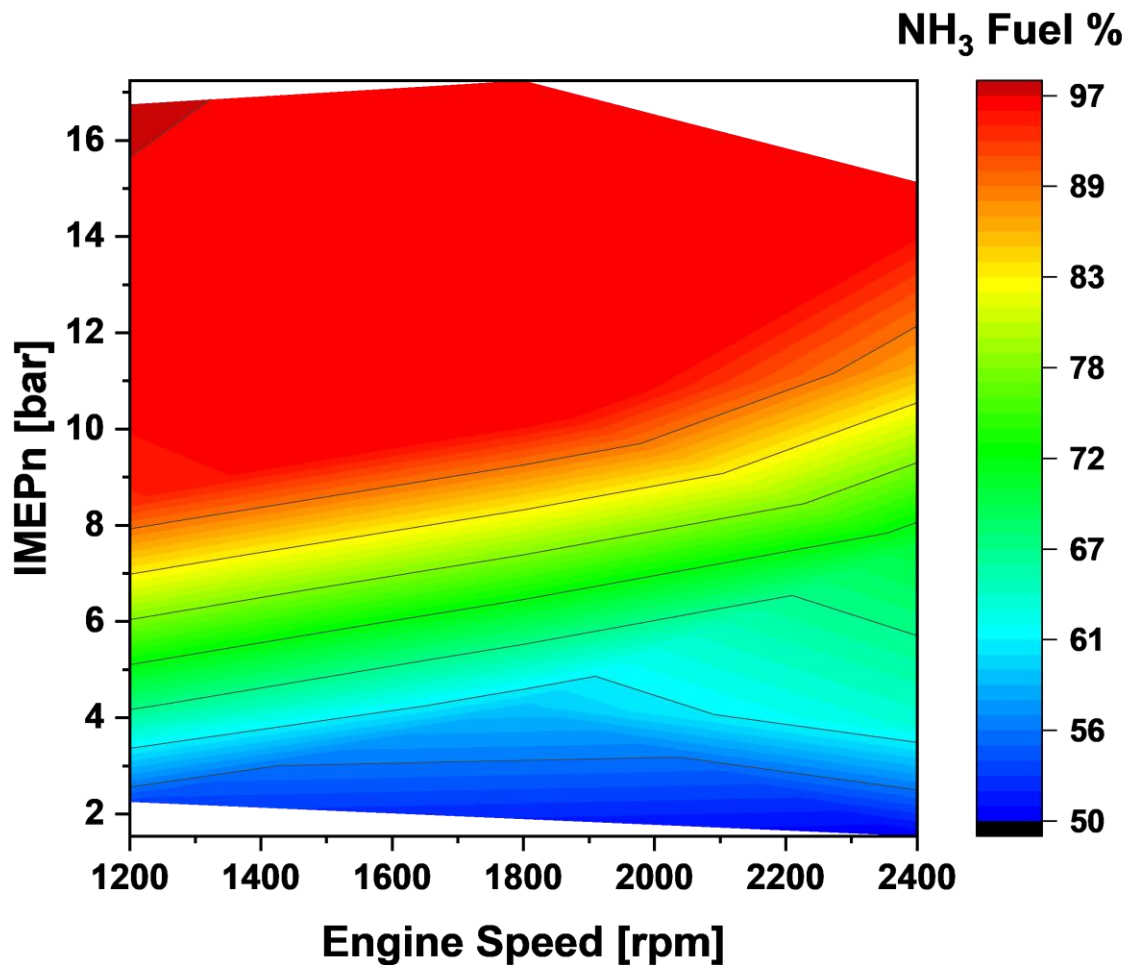


High engine-out NO_x & NH_3

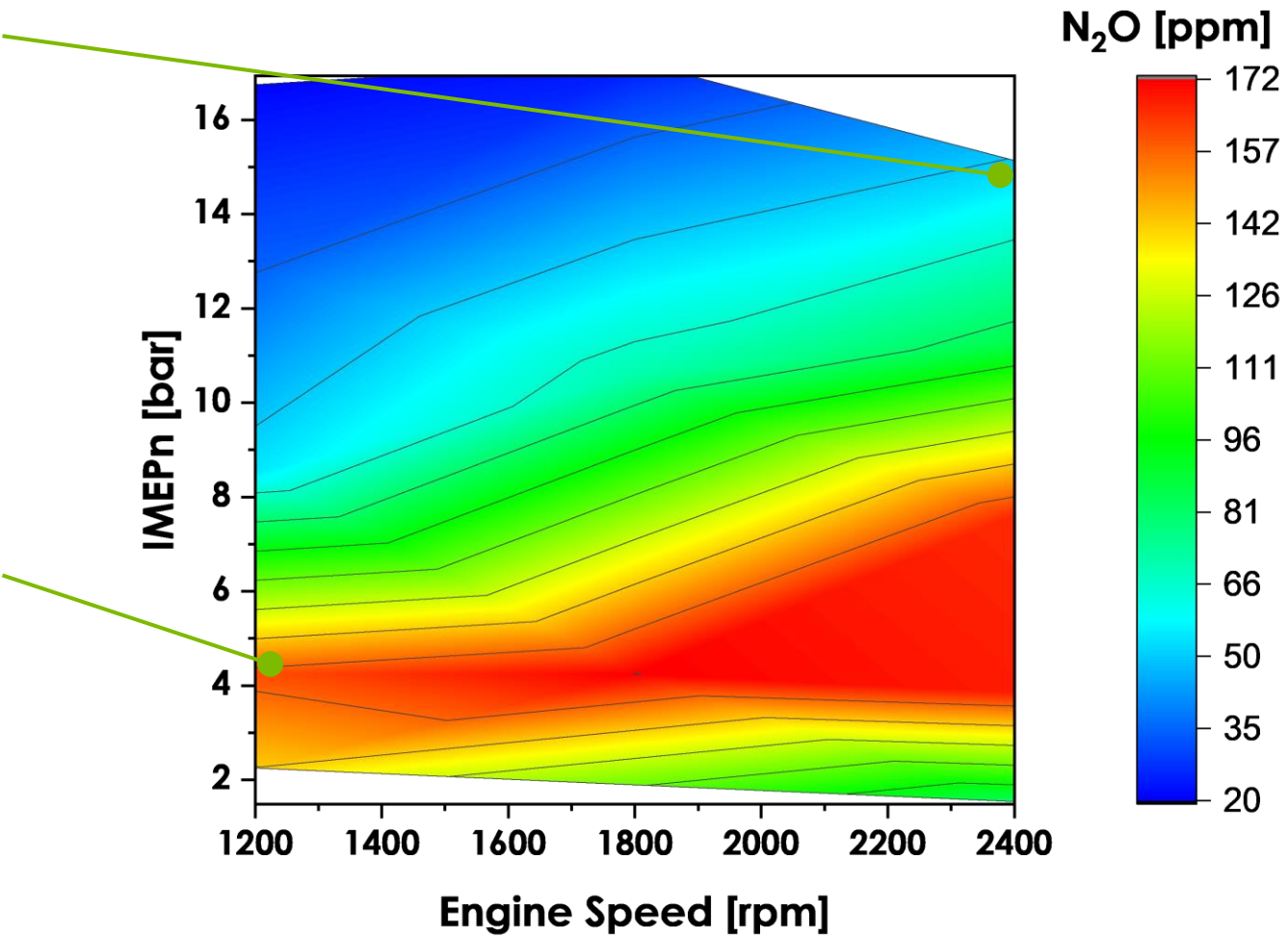
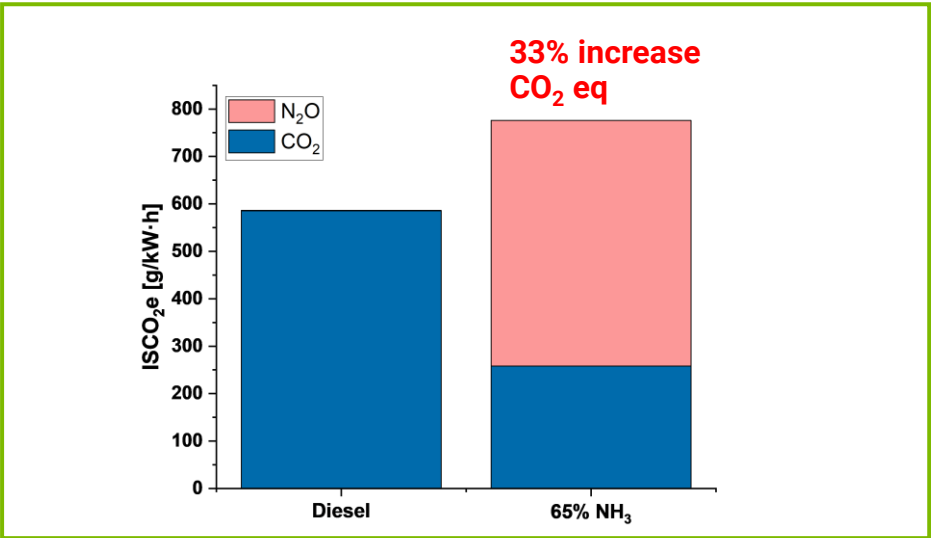
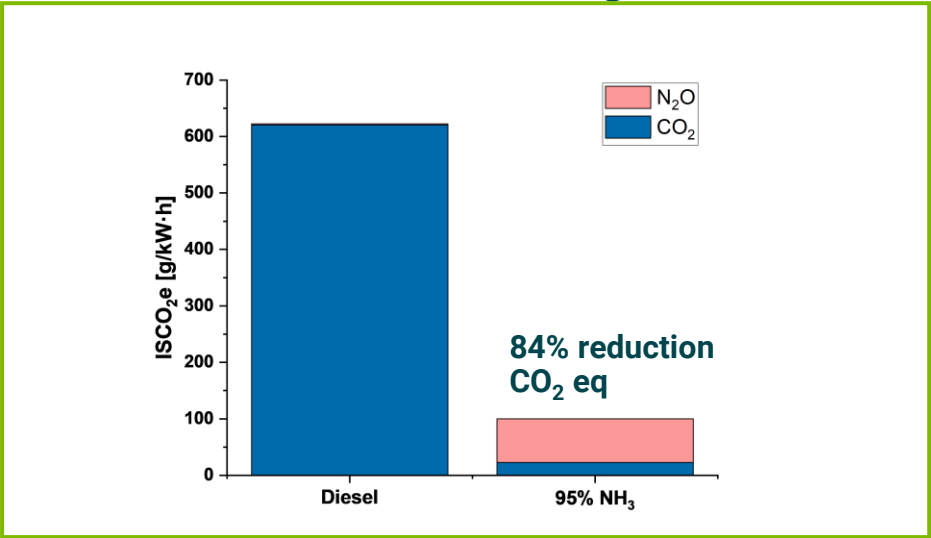


> 90% engine-out GHG reduction at high load

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

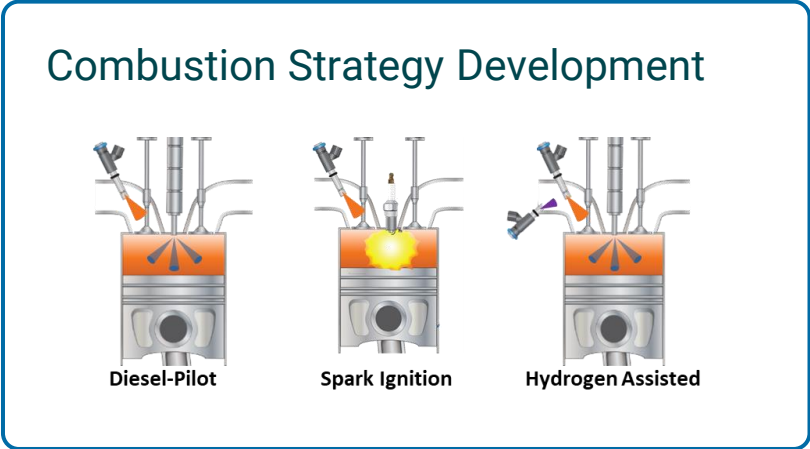


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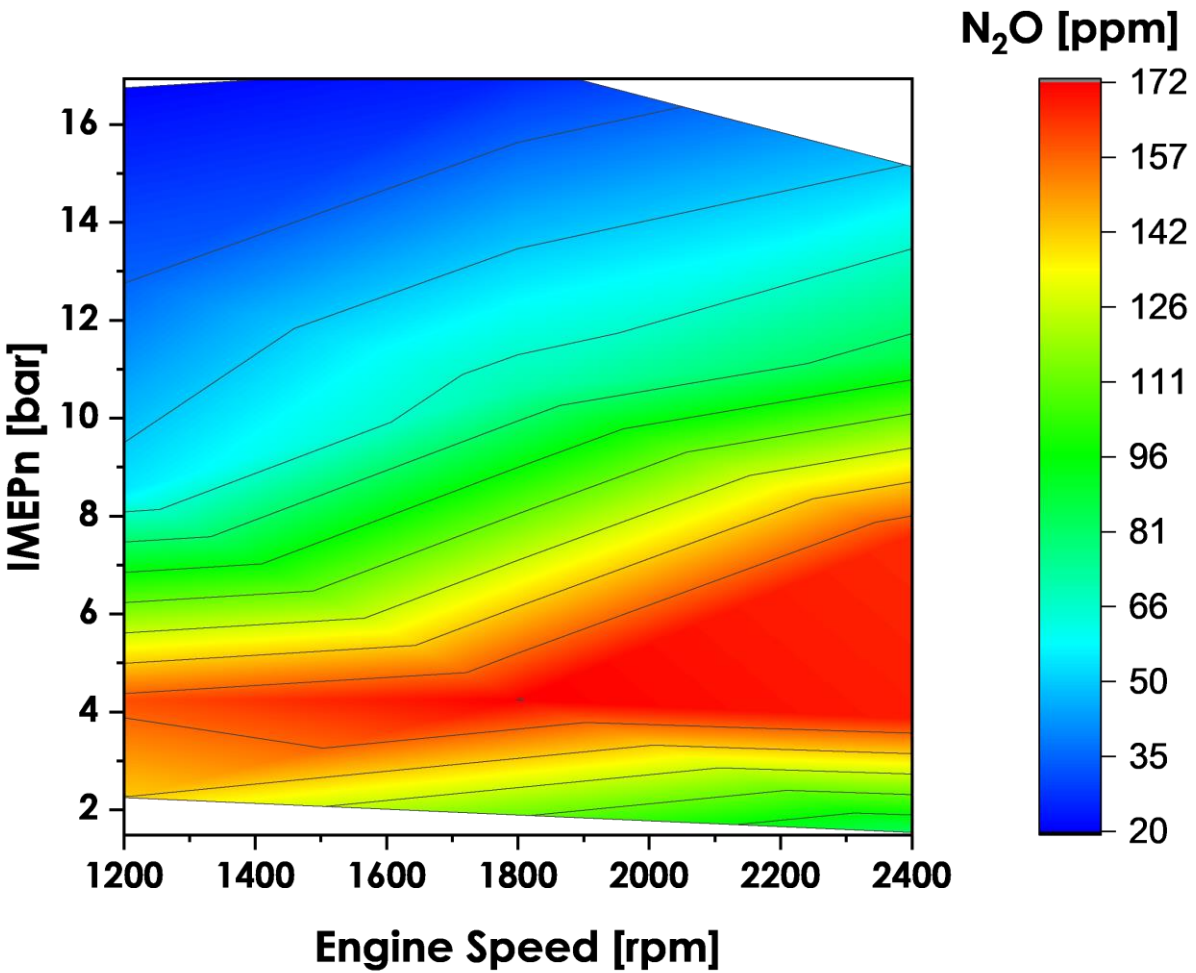


(N_2O = 273x more potent GHG than CO_2)

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



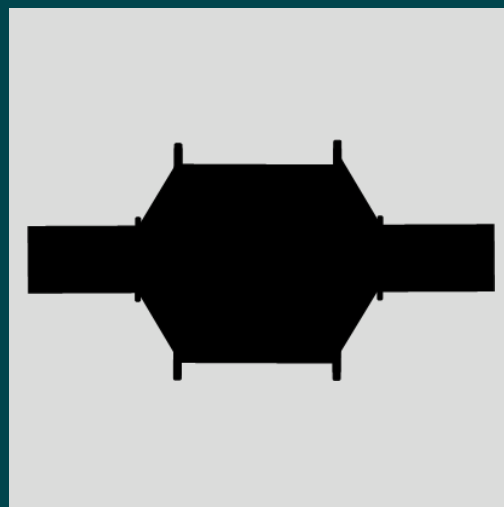
- Air-to-fuel ratio
- Injection schedule
- Modeling



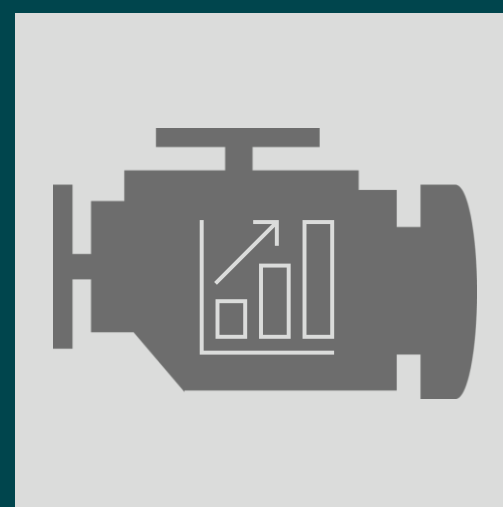
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Engine Mapping



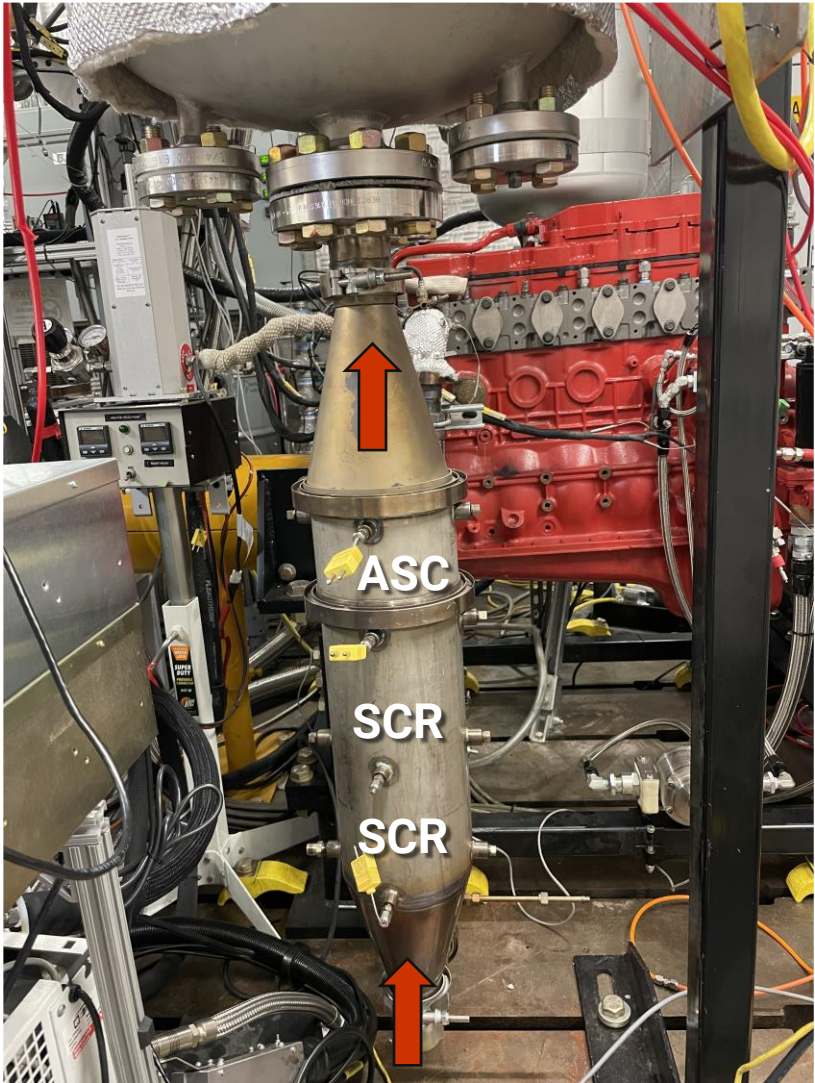
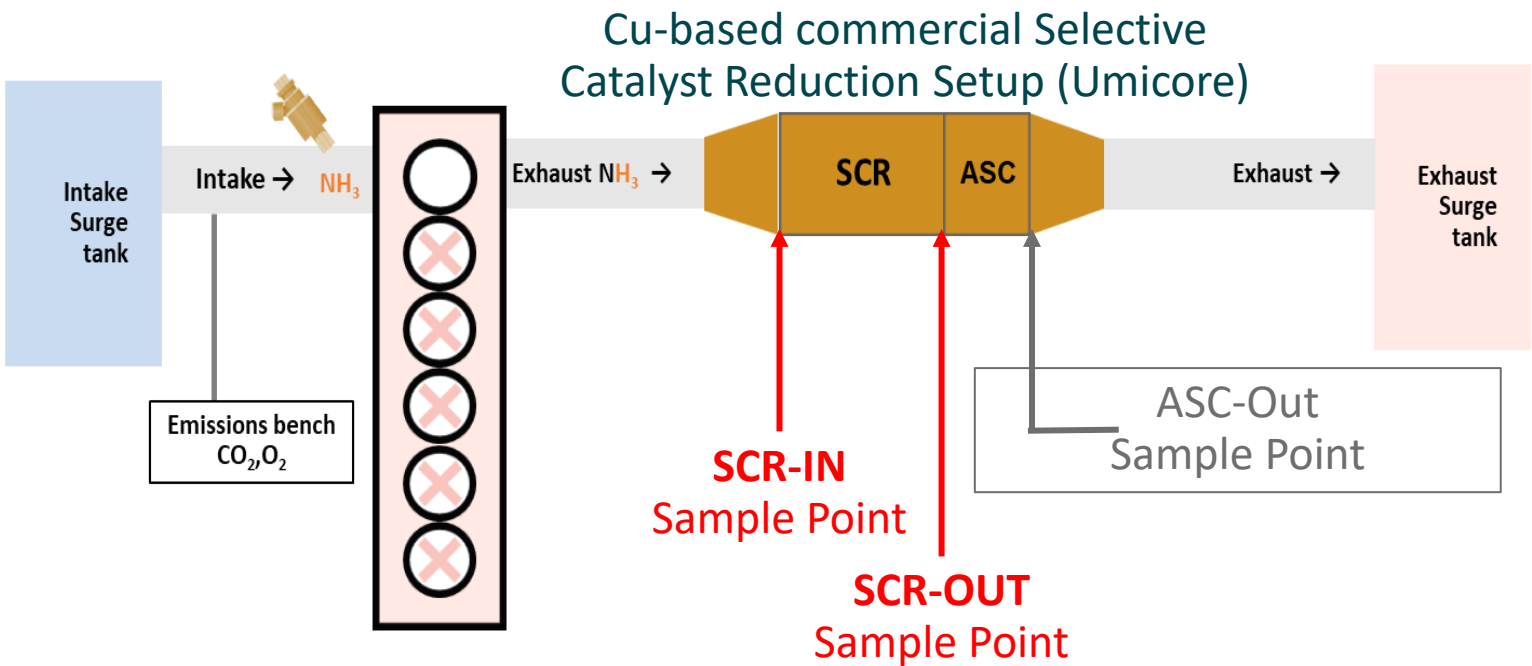
**Aftertreatment &
Emissions Impacts**



**Thermodynamic
Efficiency**

Commercial SCR + ASC aftertreatment system has been installed

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

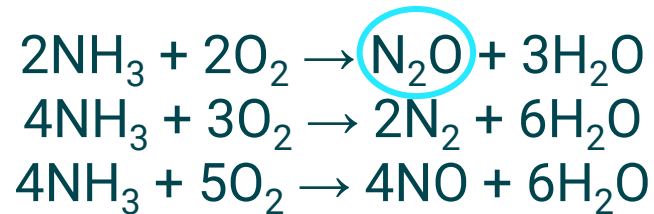


Selective catalytic reduction uses ammonia to reduce NO_x

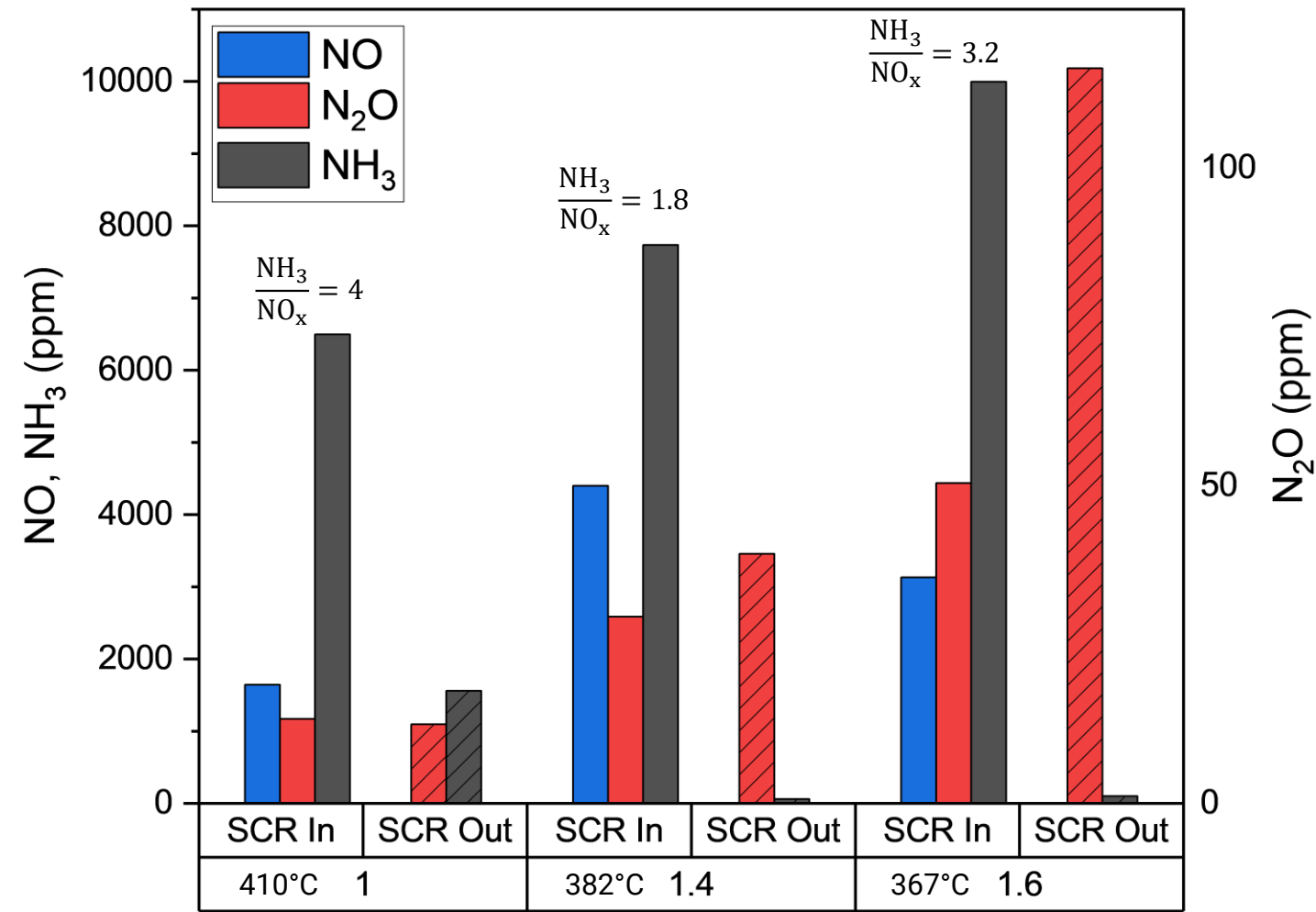


$$\frac{\text{NH}_3}{\text{NO}_x} = 1 \text{ (Ideal stoichiometry)}$$

Competing NH₃ Oxidation Pathways

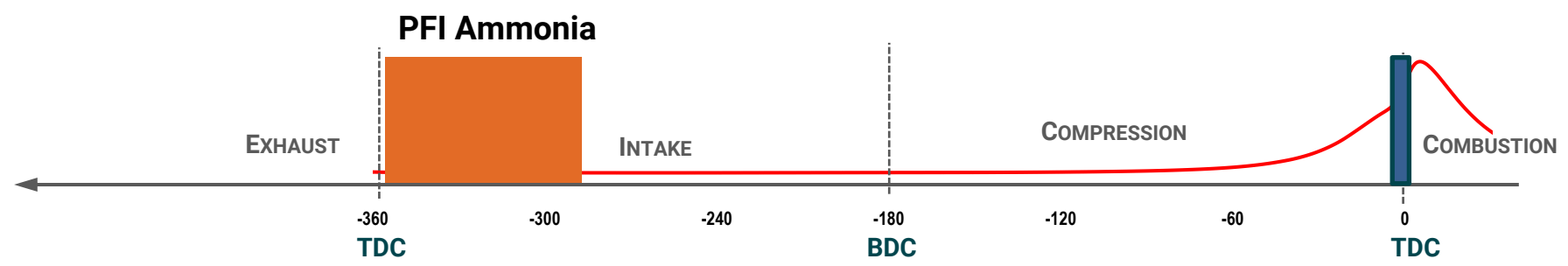


Initial SCR results show potential for NO_x, NH₃ abatement, depending on operating conditions. Optimization needed.

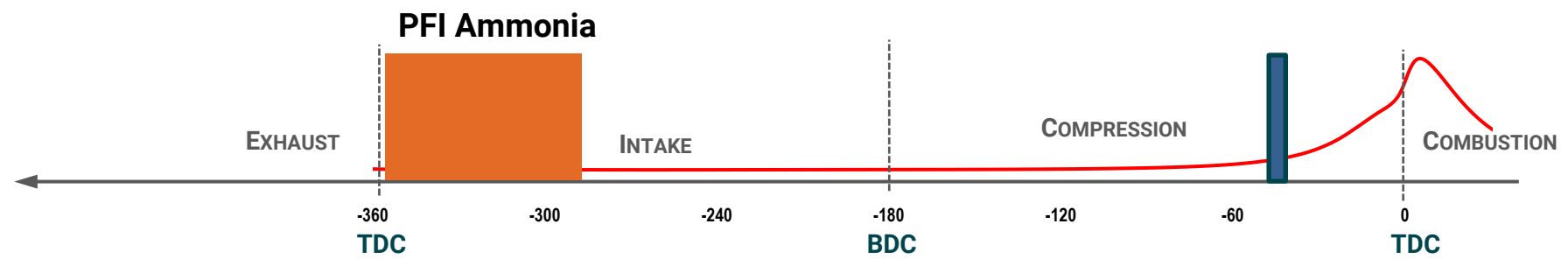


Ammonia dual-fuel direct injection strategies

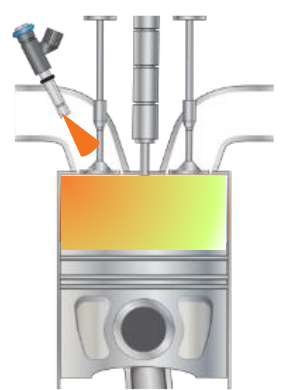
Low-pressure dual-fuel engine (4-stroke) with direct injection pilot fuel



Conventional diesel timing (late pilot)



Early pilot



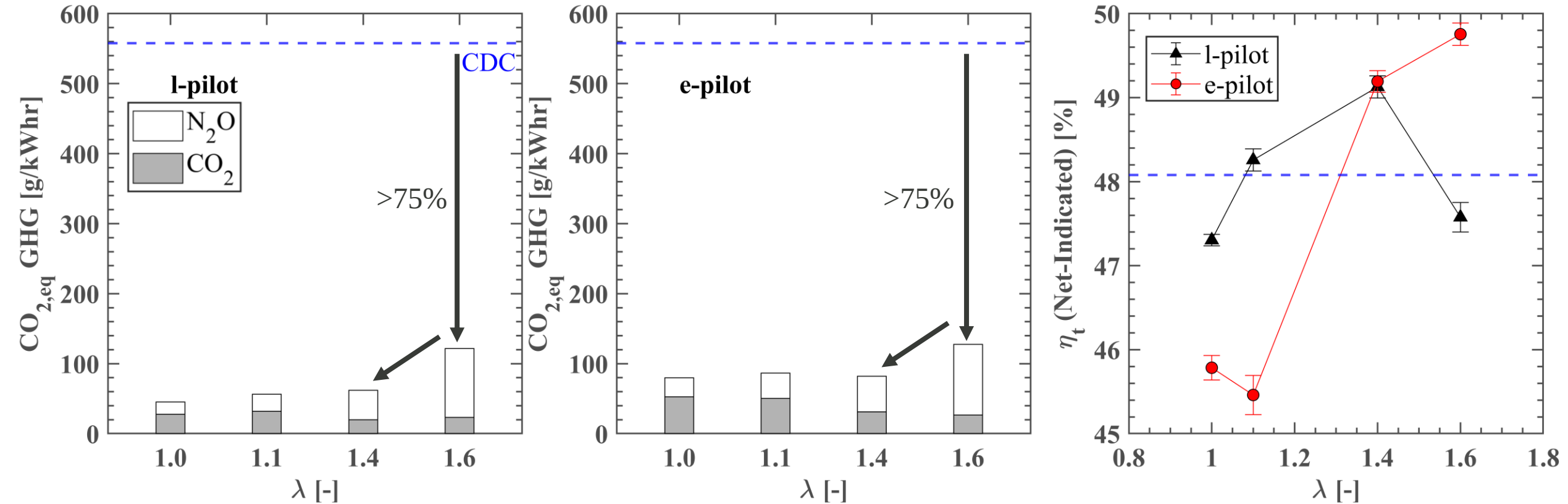
Ammonia Port Injection



Diesel Direct Injection

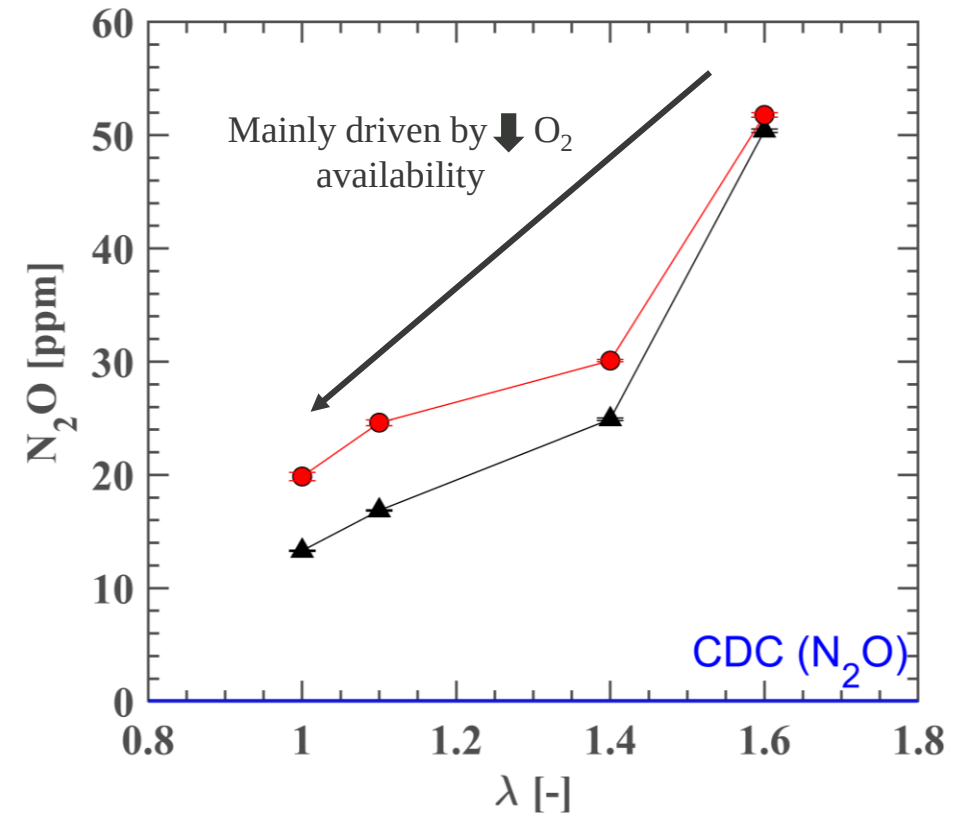
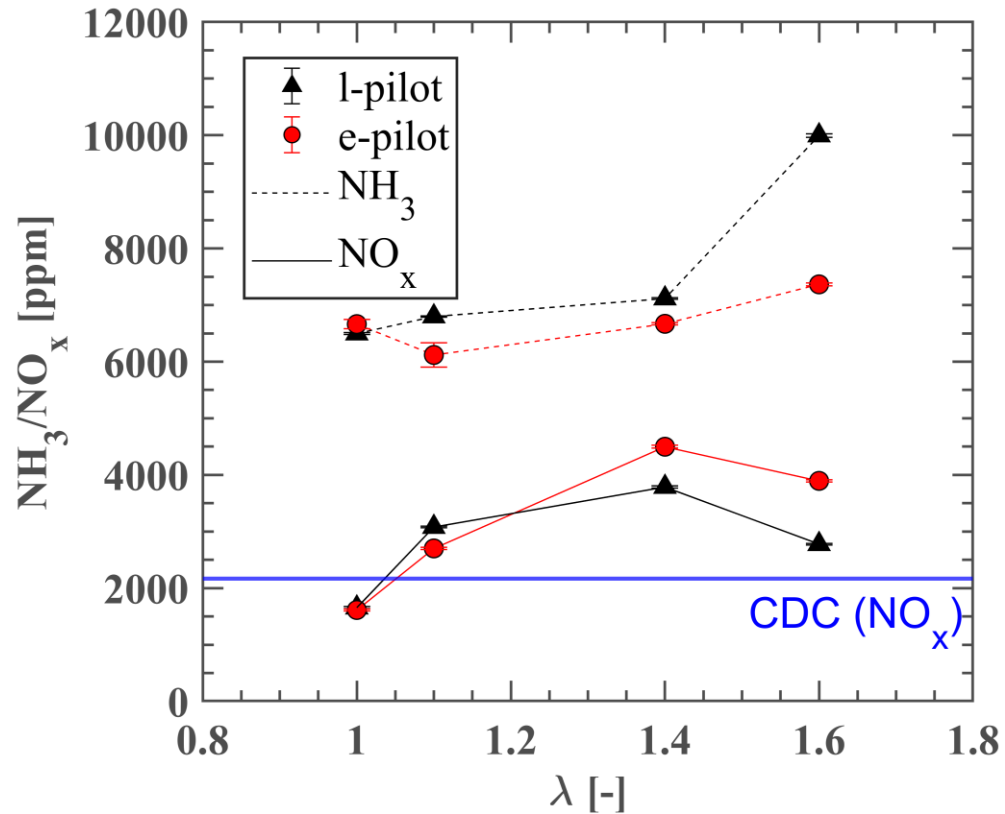
Diesel-like η_t and further reduction of N_2O possible with richer l-pilot and e-pilot conditions

1200 rpm, ~12.6 bar IMEP

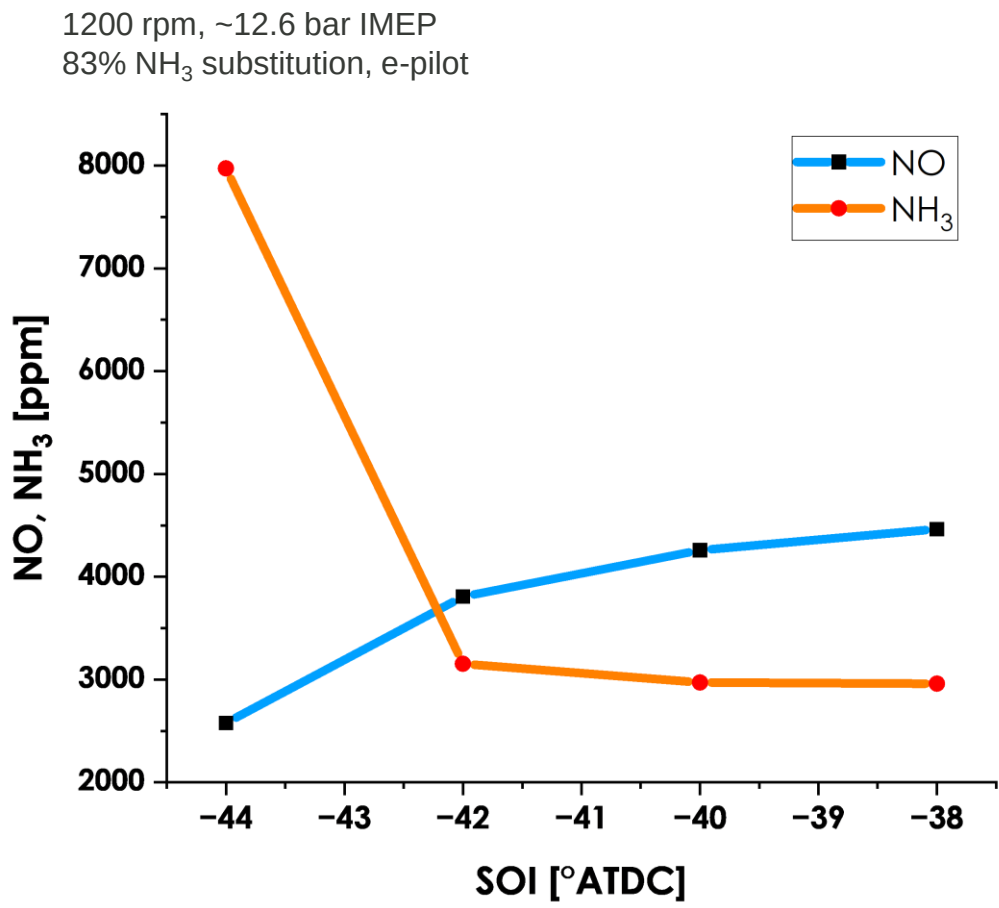


NO_x reduction without significant NH_3 slip over an SCR requires optimization; reduced N_2O formation at $\lambda < 1.6$

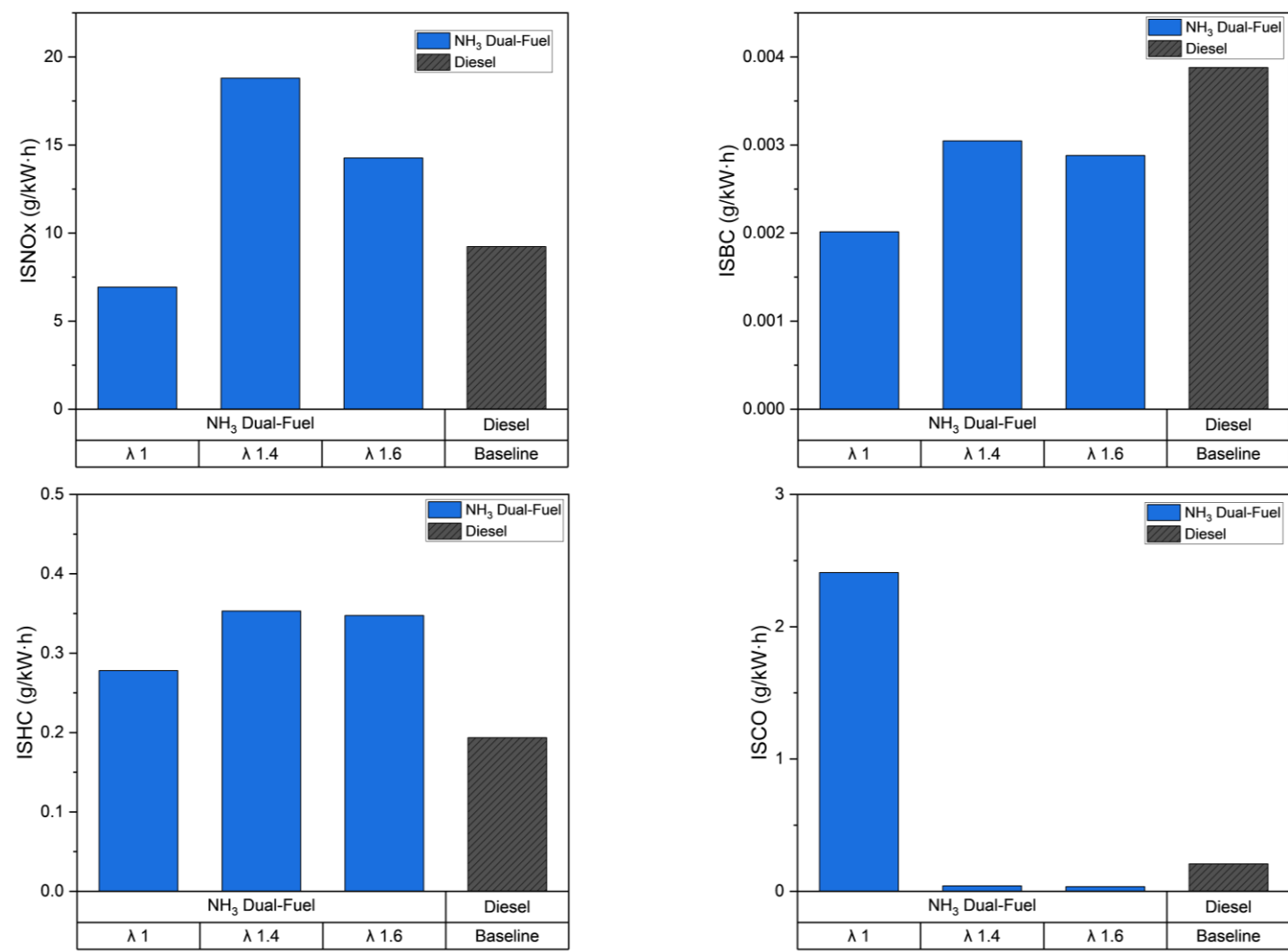
1200 rpm, ~12.6 bar IMEP



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

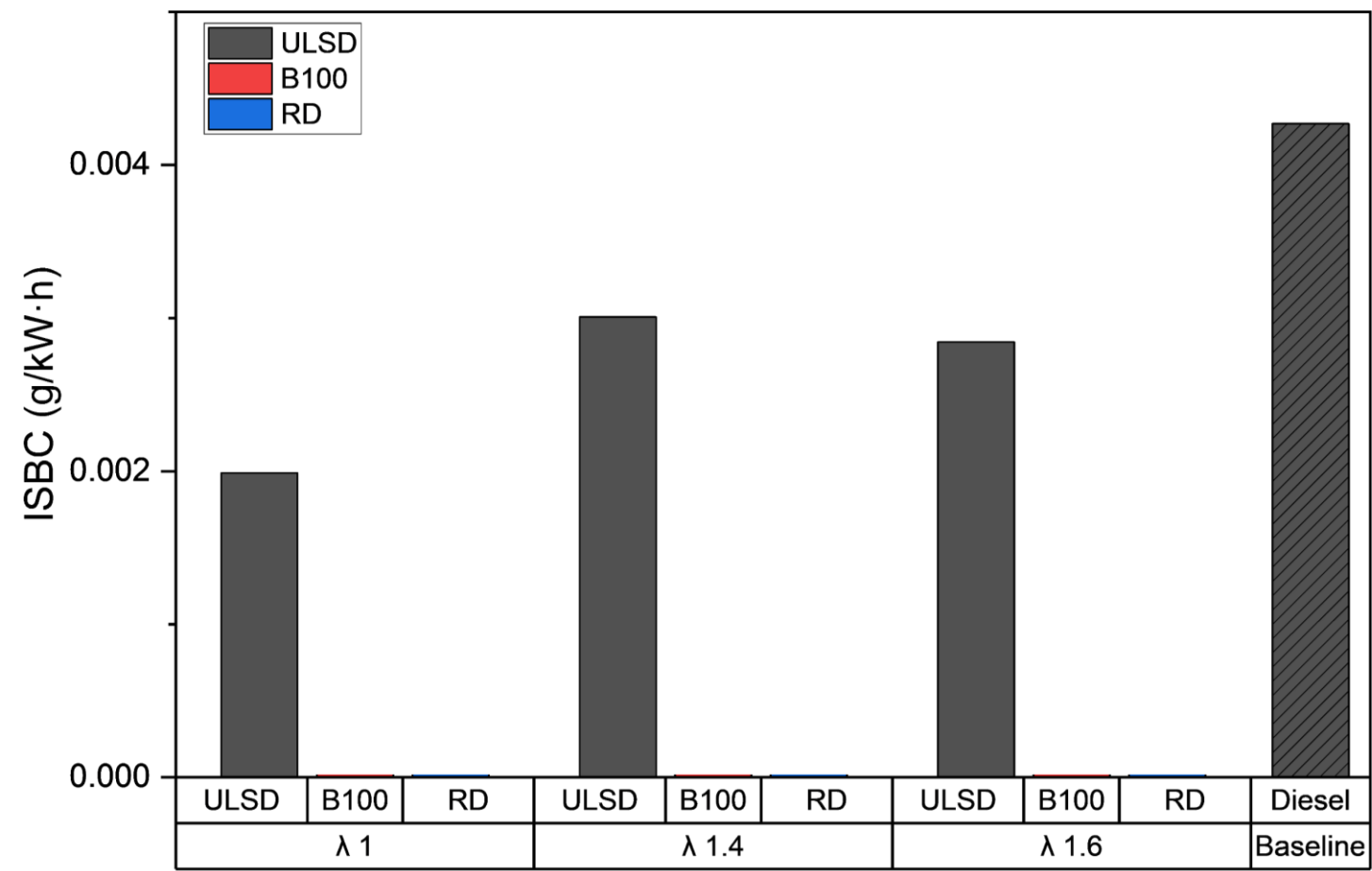


NH₃ dual-fuel combustion impacts engine-out criteria emissions: aftertreatment needed



1200 rpm, ~12.6 bar IMEP, > 90% NH₃ substitution, I-pilot

Soot reduction is far less than linear with diesel displacement



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?

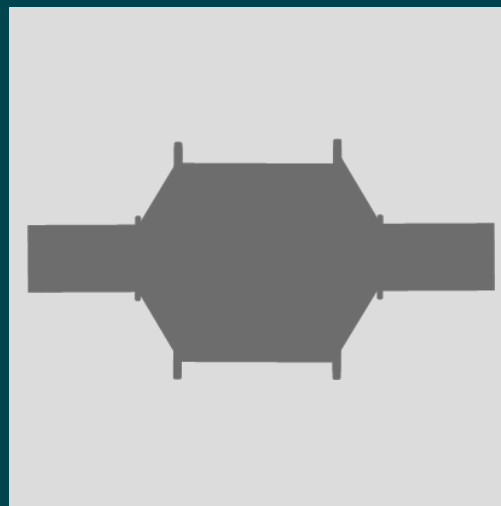
B100 (FAME) and RD (paraffinic) lack PAH found in ULSD

B100 also has 11% oxygen content

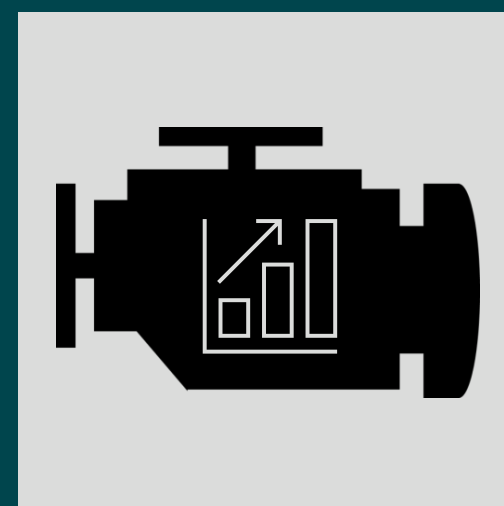
Fuel	Cetane Number	Density [g/cc]	LHV [MJ/kg]
NH ₃	~ 0	0.609	18.8
ULSD	40.8	0.856	42.2
B100	54.1	0.884	37.3
RD	84.9	0.786	43.8



Engine Mapping

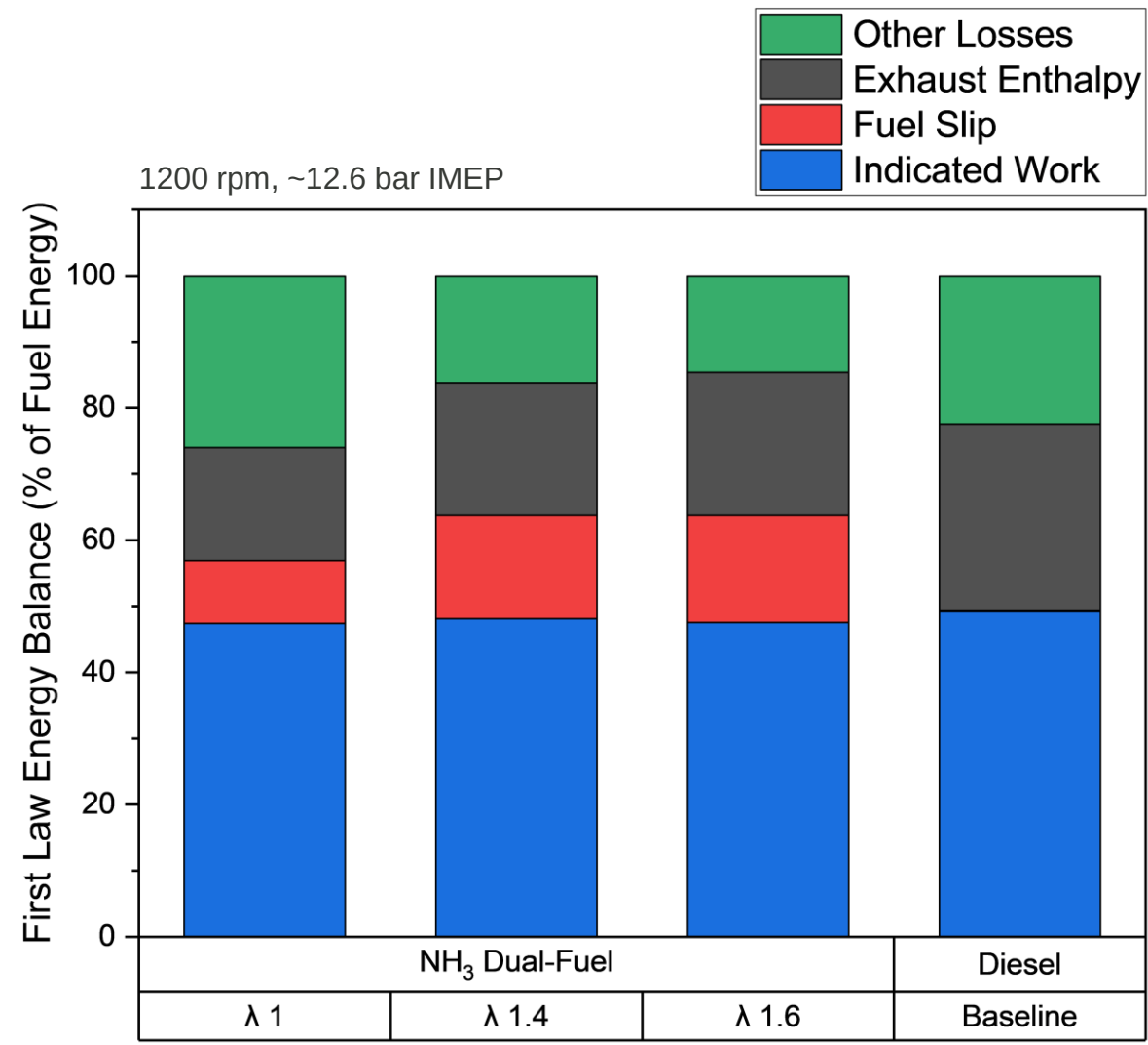


**Aftertreatment &
Emissions Impacts**



**Thermodynamic
Efficiency**

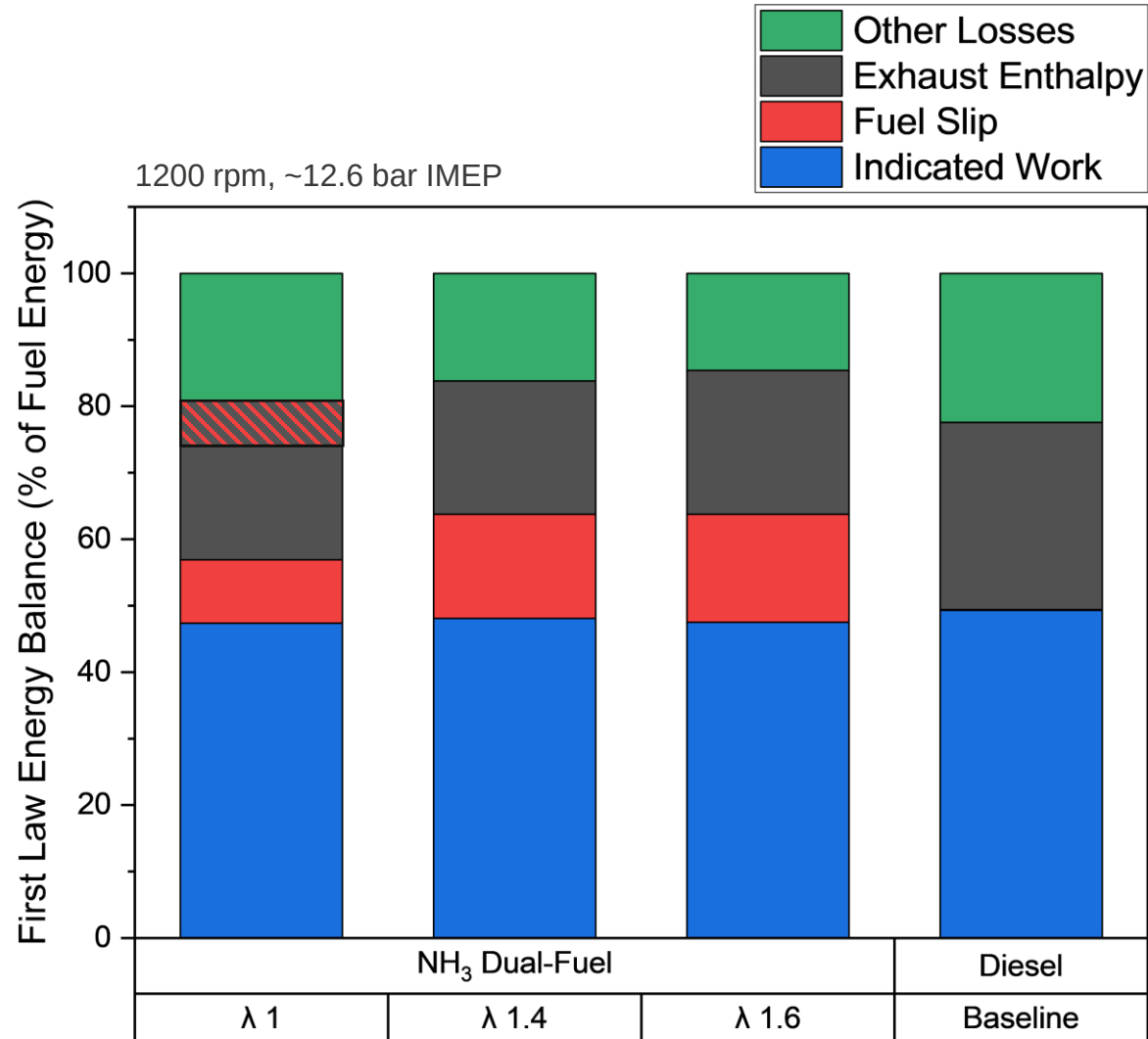
Engine efficiency for NH₃ dual-fuel is equivalent to diesel for dual-fuel NH₃ λ sweep with late pilot injection timings



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	$\lambda = 1$: 9°BTDC $\lambda = 1.4, 1.6$: 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

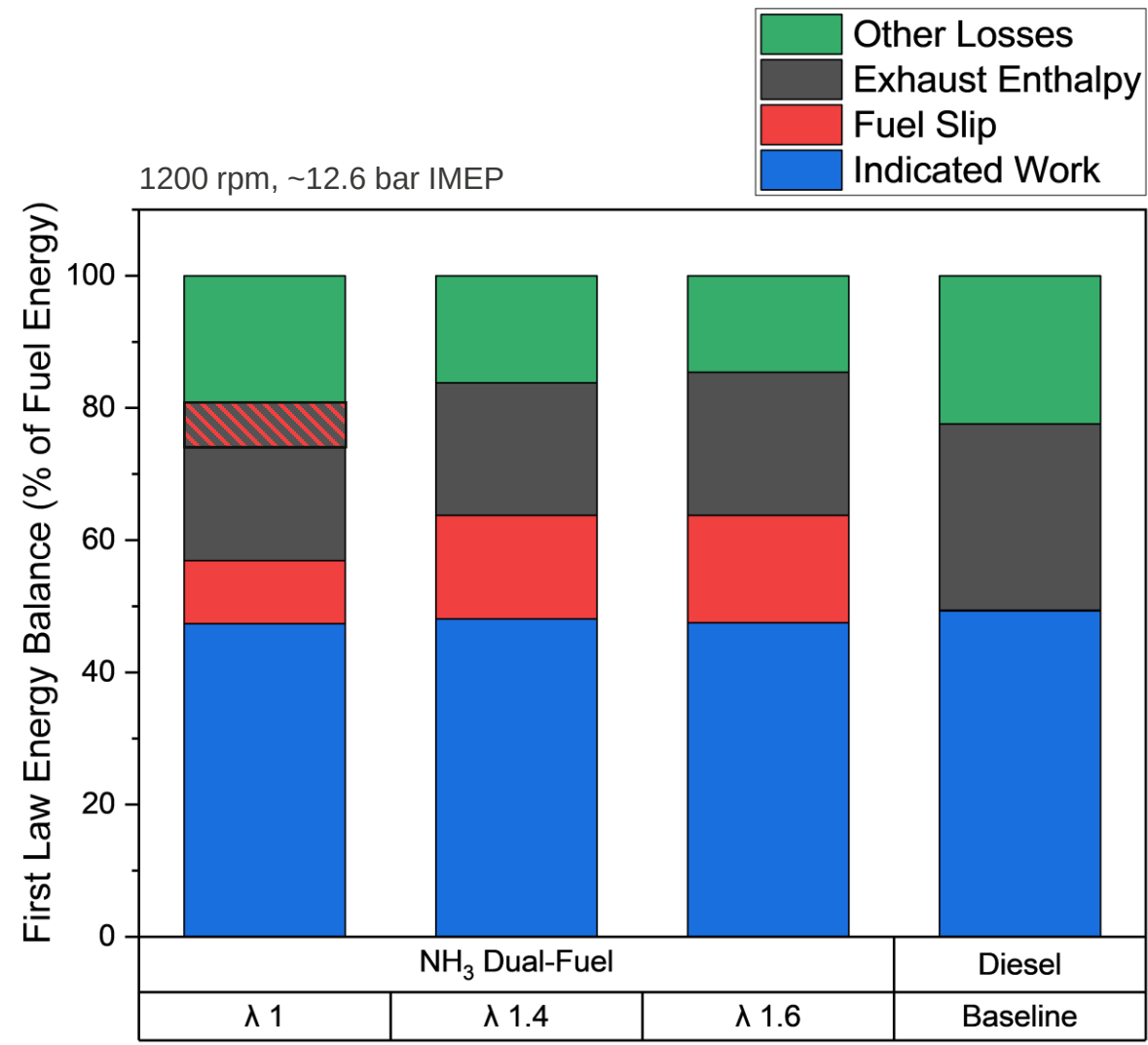
For stoich case, 10% of fuel unburned, but change not reflected in efficiency

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

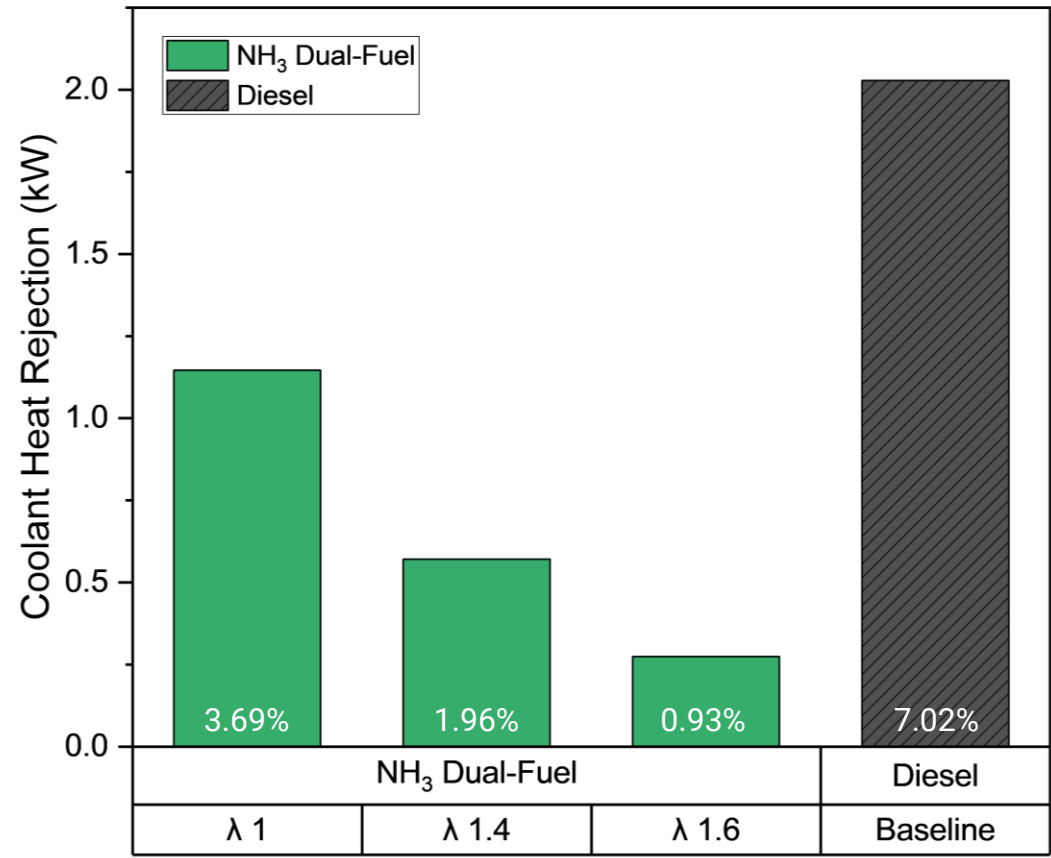
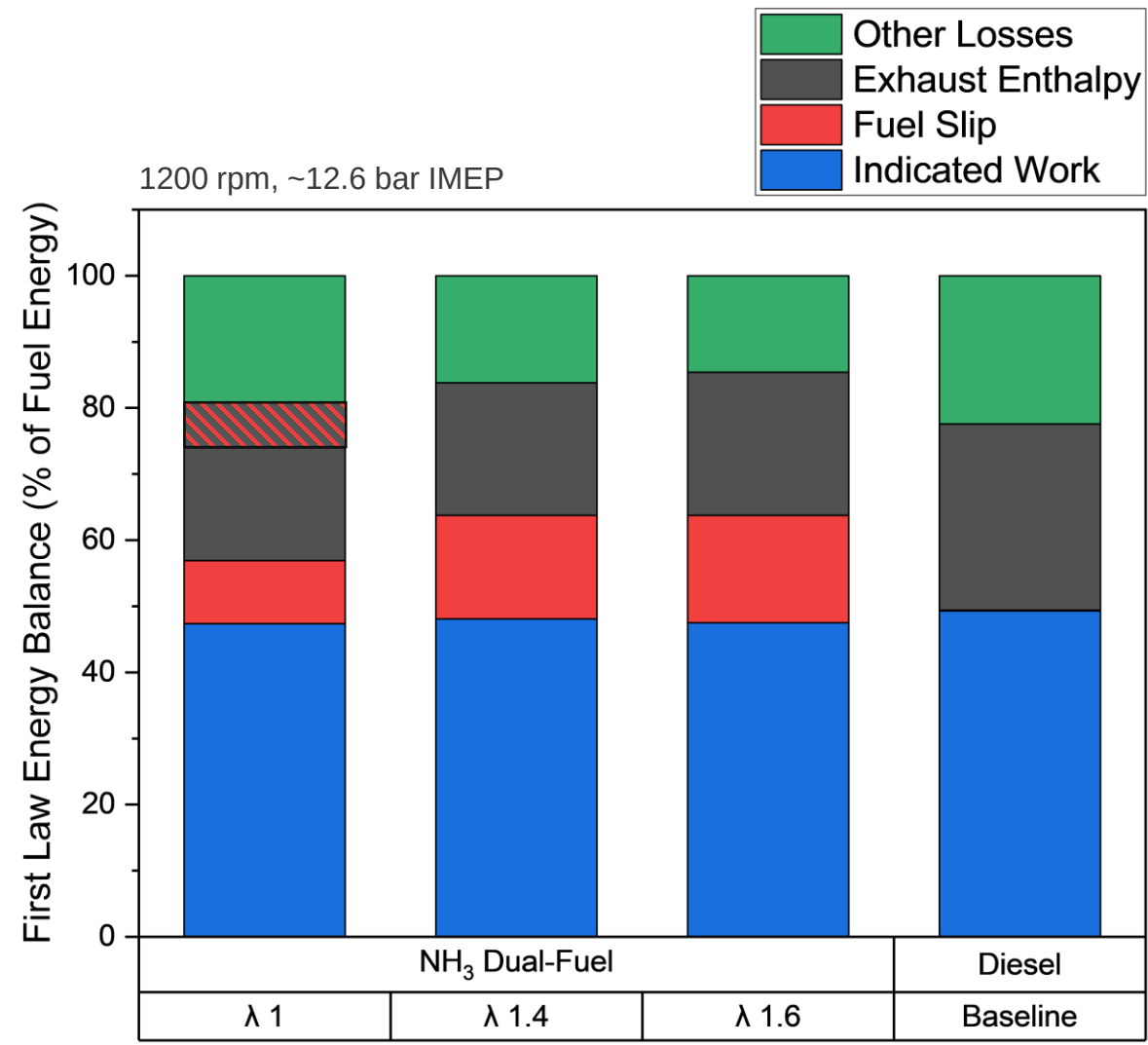
Other losses is the balance term and comprises heat transfer to coolant/oil/room as well as other unaccounted-for losses



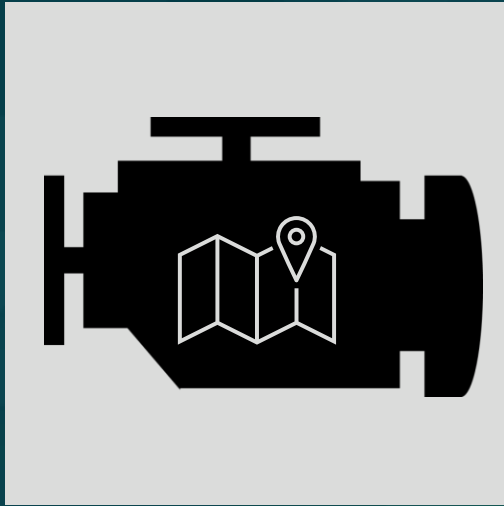
This is a full multi-cylinder engine converted to run on one cylinder

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 NH₃ dual-fuel operation relative to diesel

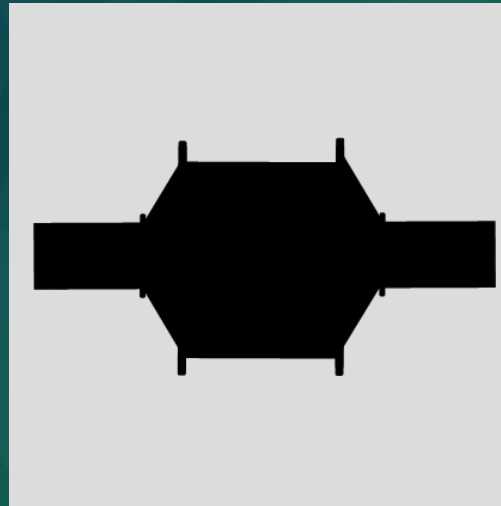


Questions?

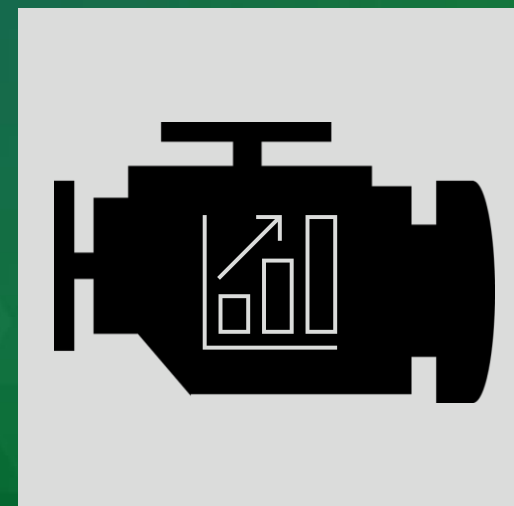


**Dual-fuel approach
effective for high NH_3
substitution**

**Combustion development
needed at low loads**



**SCR shows potential for
 $\text{NH}_3 + \text{NO}_x$ cleanup
 N_2O formation is a
concern**



**Thermal efficiency
equivalent to diesel
Reduced heat transfer**