Developing Fuel Injection Strategies for Using Ammonia in Direct Injection Diesel Engines

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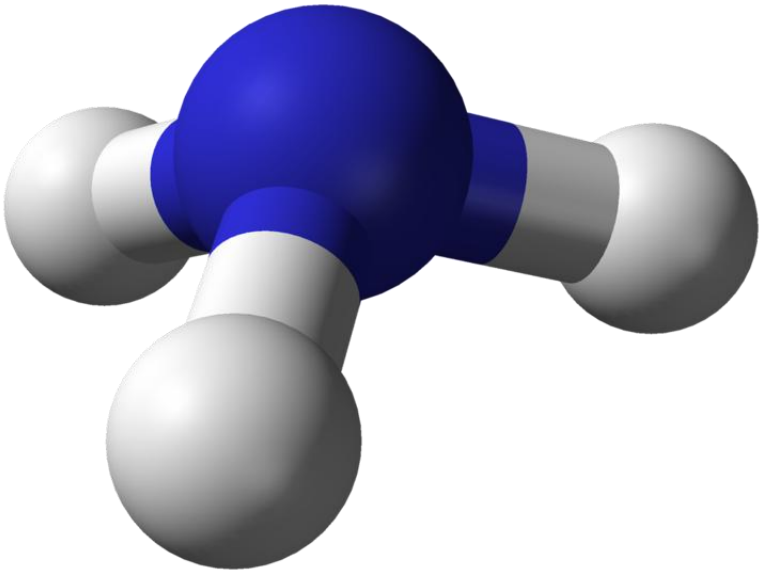
Agenda

- Background information
- Previous project
- Update on current test activity



Background

- Motivation
  - Ammonia (NH_3) combustion does not generate CO_2
  - Hydrogen carrier, renewable, etc.

- Challenges
  - Ammonia is very difficult to ignite
    - Octane number ~ 130
    - Autoignition T ~ 651 ºC (gasoline: 440 ºC; diesel: 225 ºC)
    - High latent heat of vaporization ~ 1370 kJ/kg (gasoline: 380 kJ/kg; diesel: 375 kJ/kg)
    - Narrow ignition limits ~ 16 – 27 %-v in air
    - High vapor pressure ~ 10 bar @ ambient temperature
  - Ammonia flame temperature is lower than diesel flame T
  - Erosive to some materials
  - Ammonia emissions can be harmful
  - Potential high NO_x emissions due to fuel-bound nitrogen

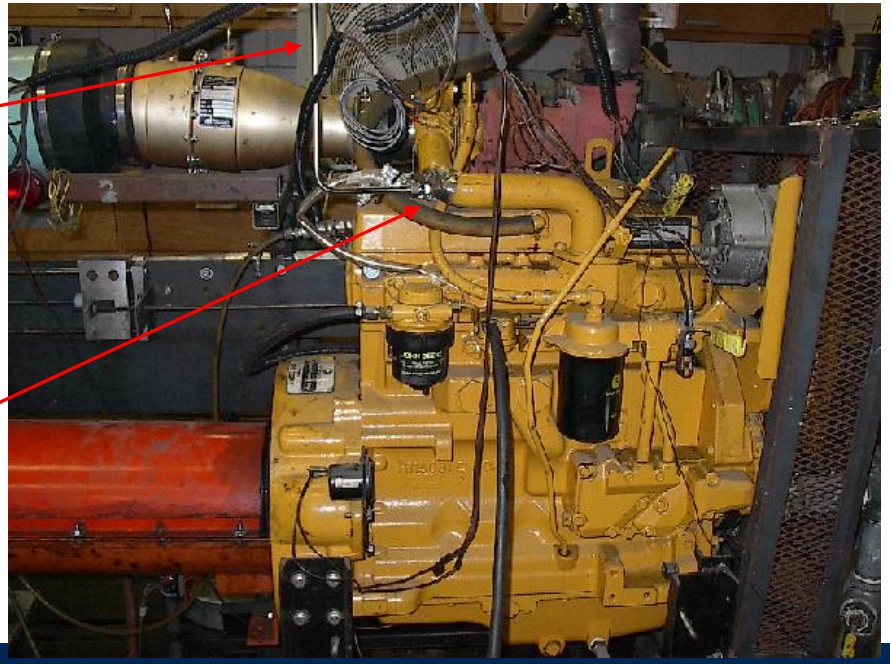
Combustion Characteristics of Various Engine Fuels

Fuel	Formula	Storage Temp. [ºC]	Storage Pressure [kPa]	Density [kg/m^3]	Lower Heating Value [MJ/kg]	Stoichiometric Air/Fuel Ratio by Weight	Energy Content [MJ/kg-stoichiometric mixture]	Autoignition Temp. [ºC]	Cetane Rating
Ethanol	C_2H_5OH	25	101.3	790	27	8.95	2.70	423	-
Gasoline	C_7H_{17}	25	101.3	700	42.5	15.29	2.58	370	-
Hydrogen (gas)	H_2	25	24,821	17.5	120	34.32	3.40	571	-
Hydrogen (liquid)	H_2	-253	102	71	120	34.32	3.40	571	-
Diesel	$C_{14.4}H_{24.9}$	25	101.3	850	45	14.32	2.77	254	40-55
Methanol	CH_3OH	25	101.3	780	19.5	6.44	2.69	464	5
Dimethyl Ether	CH_3OCH_3	25	1030	660	28.4	8.95	2.85	350	55-60
Ammonia	NH_3	25	1030	600	18.8	6.05	2.64	651	-

- Although ammonia has a fairly low heating value – its energy content per unit mass of stoichiometric mixture is comparable to conventional gasoline and diesel fuels.
- Ammonia has superior energy-density over hydrogen.

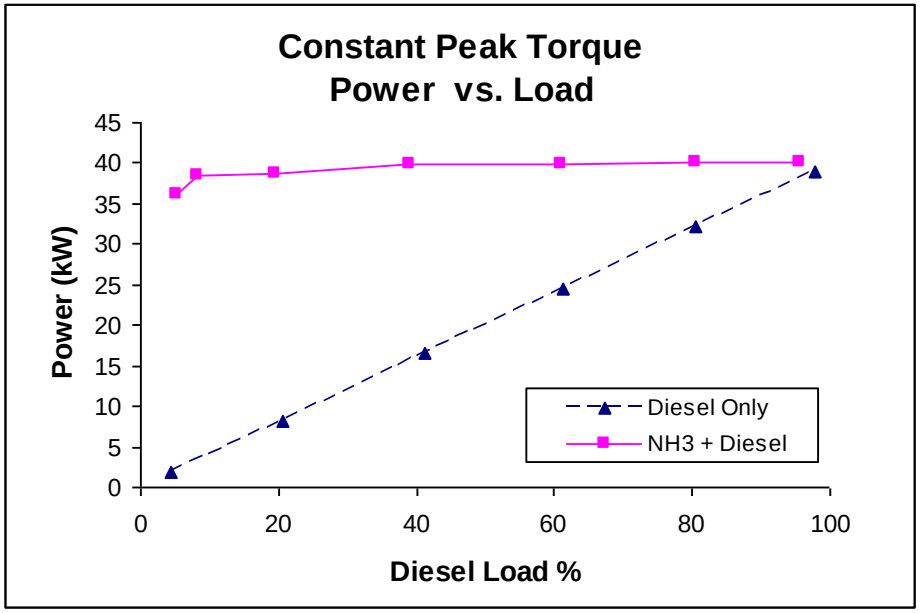
History of Ammonia as an Engine Fuel at ISU

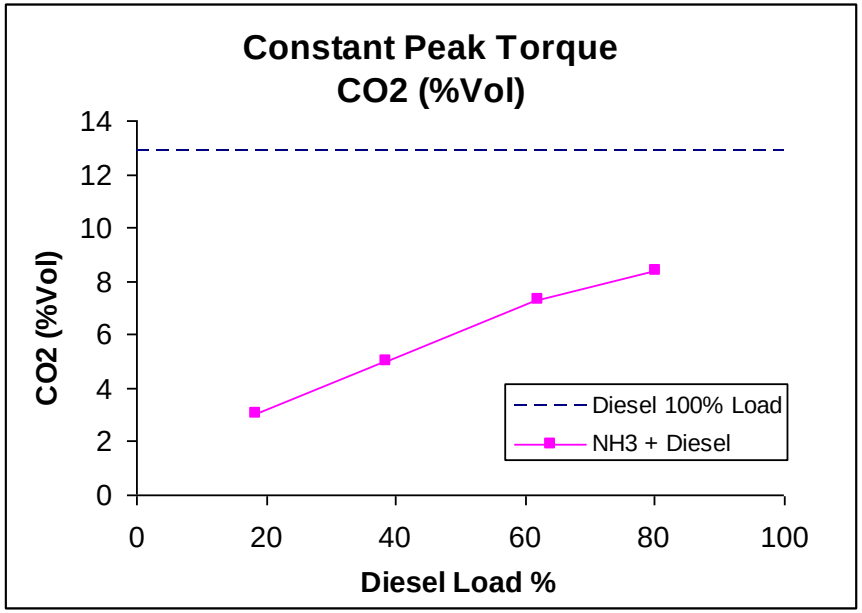
- Dual fueling of ammonia and diesel fuel
  - Introduce ammonia$_{(g)}$ to the intake manifold
  - Create premixed ammonia/air mixture in the cylinder
  - Inject diesel (or biodiesel) to initiate combustion
  - No modifications to existing diesel injection system



Engine Test Results

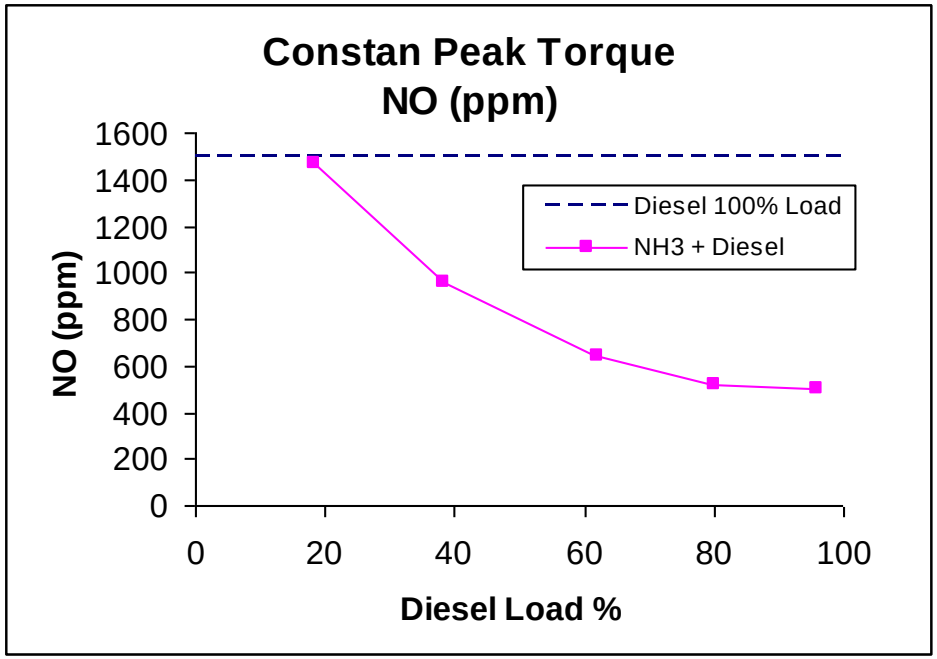
- Obtained stable engine power output
- Low CO_2 emissions
- Reasonable fuel economy between 40~60% diesel fueling
- Ammonia combustion efficiency ~ 95%

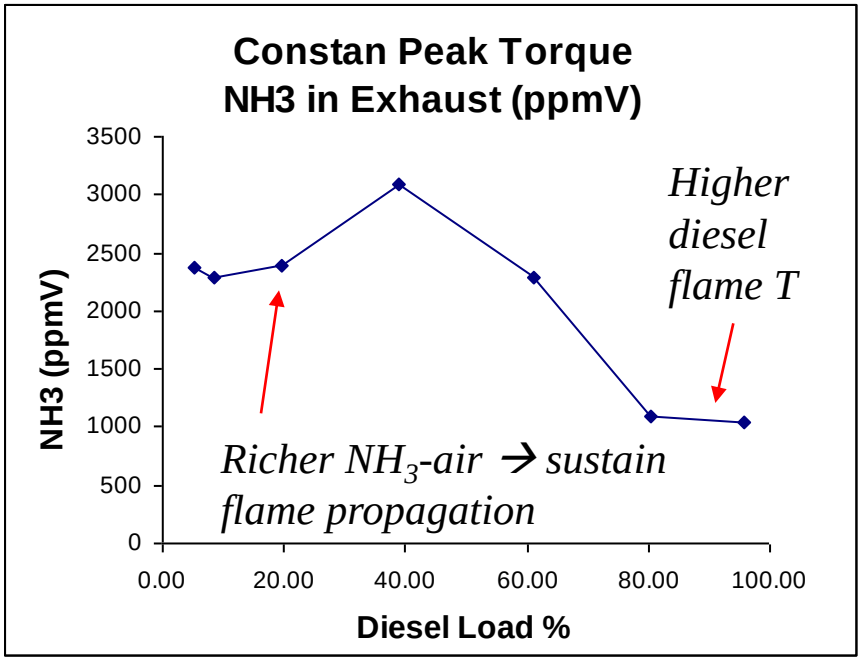




NO & NH_3 Emissions

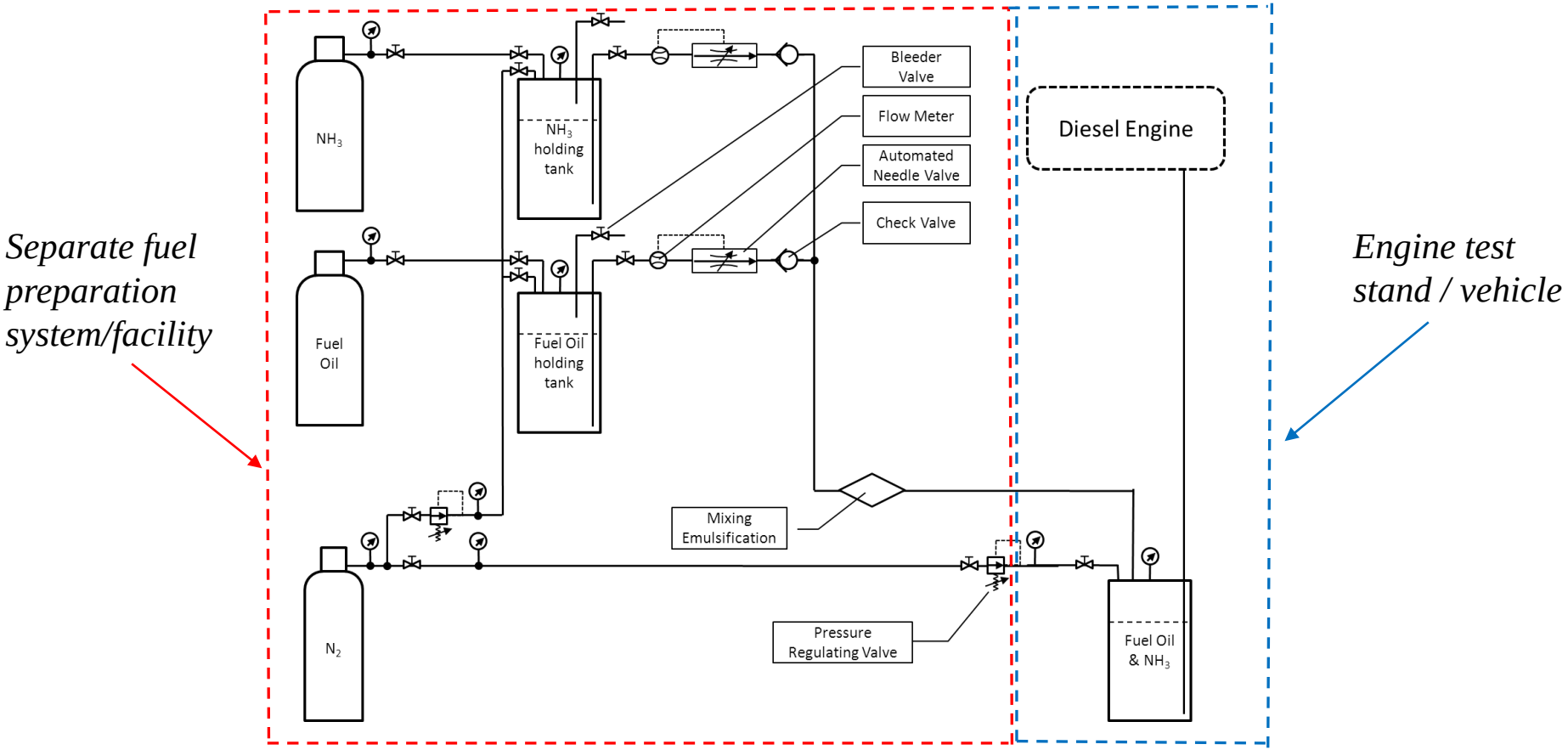
- NO emissions are comparable or less than engine operation on regular diesel
- Overall high ammonia emissions – some might also be caused by positive valve overlap in combination with boosted engine operation.





Experimental Setup: Fuel Preparation

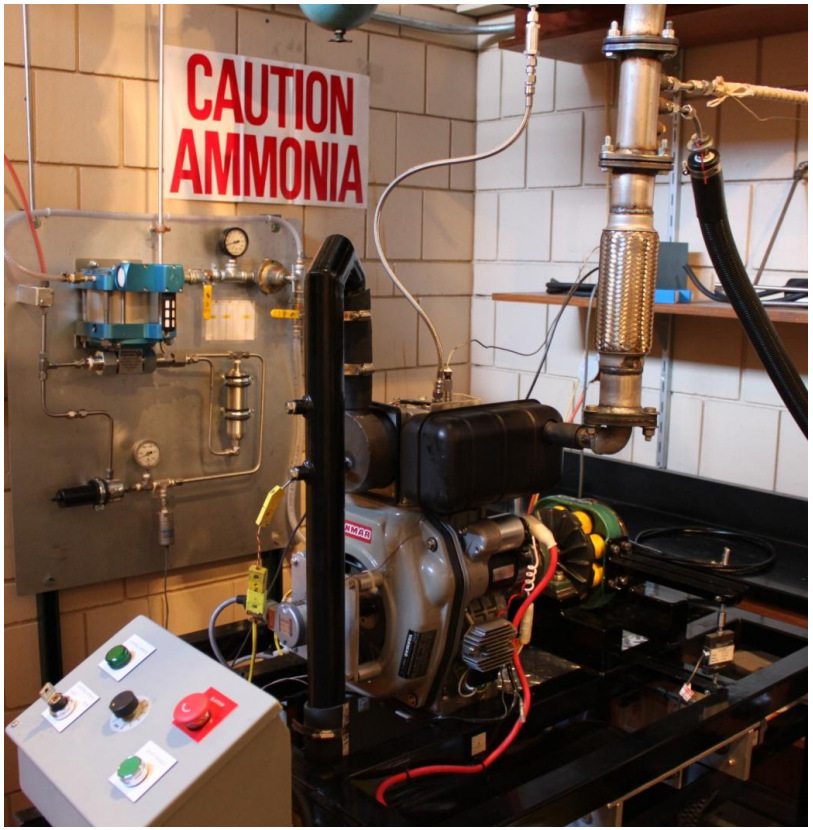
- Ammonia and a secondary fuel are mixed in a separate facility (no longer part of vehicle)



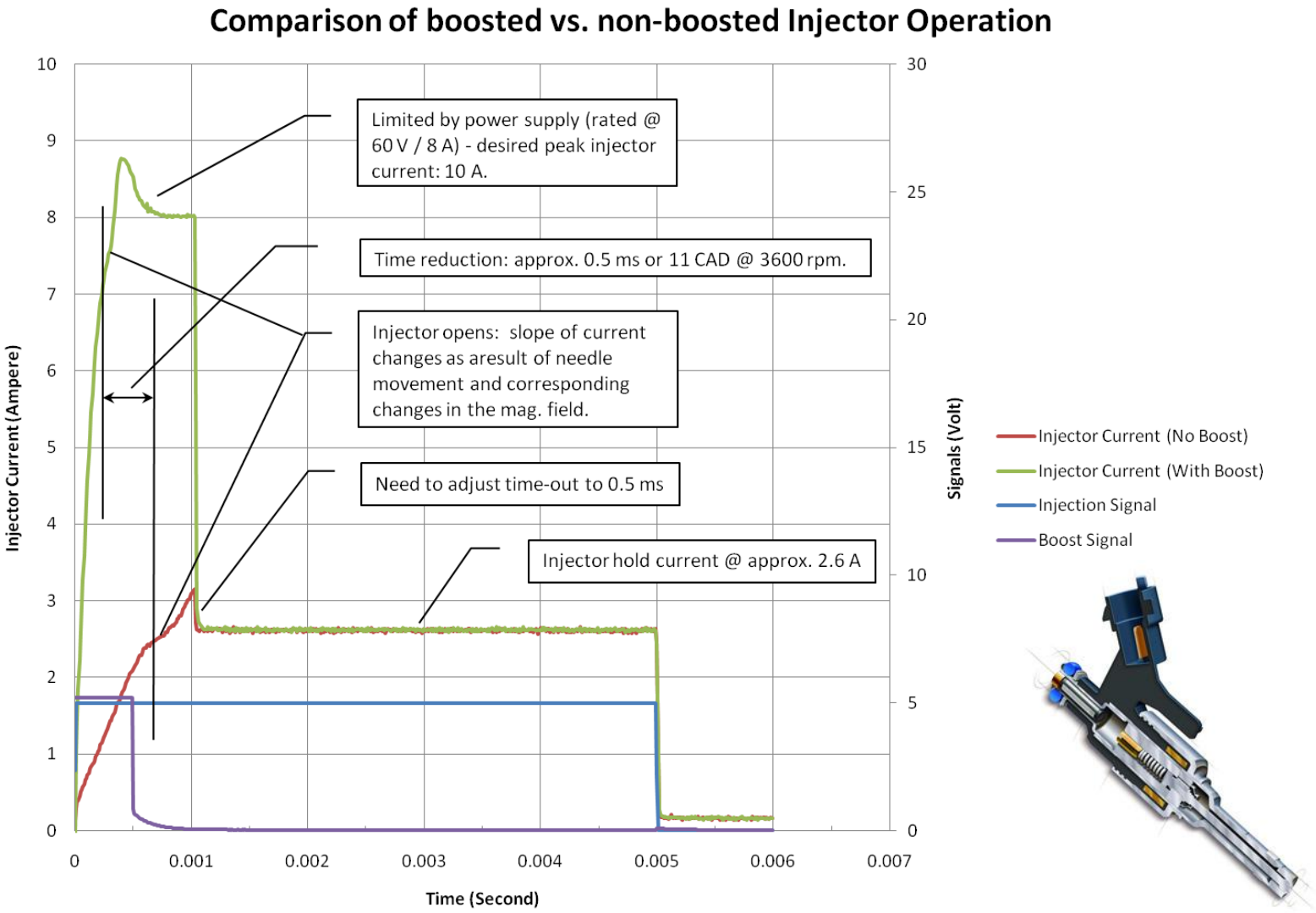
Experimental Setup: Engine

- Yanmar single cylinder direct injection diesel engine
- Custom fuel injection system

Engine Model	Yanmar L70V
Engine Type	Air Cooled, Four Stroke, Compression Ignition
Combustion Type	Direct Injection
Cylinder Arrangement	Vertical
Type of Aspiration	Natural Aspiration
Bore x Stroke (mm)	78 x 67
Compression Ratio	20:1
Total Displacement (cm^3)	320
Valves per Cylinder (Int./Exh.)	(1/1)
Rated Speed (rpm)	3600
Rated Power (kW)	4.3
Brake Specific Fuel Consumption at rated Output (g_{Diesel}/kWh)	268
Balancing System	Single, Counter-Rotating, Balancer Shaft
Type of Injection System	Electronically controlled
Injection Pump	External Pump
Injector Nozzle	Custom

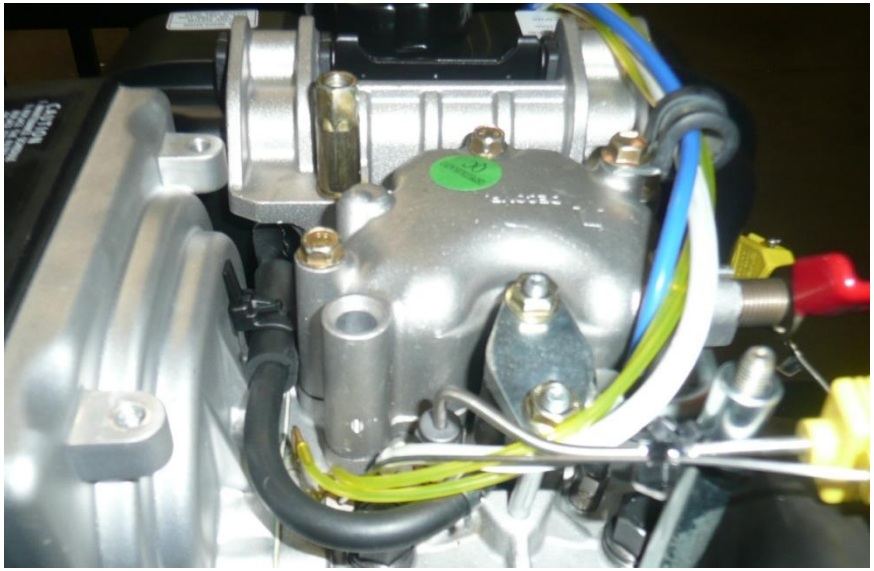


Experimental Setup: Injection System

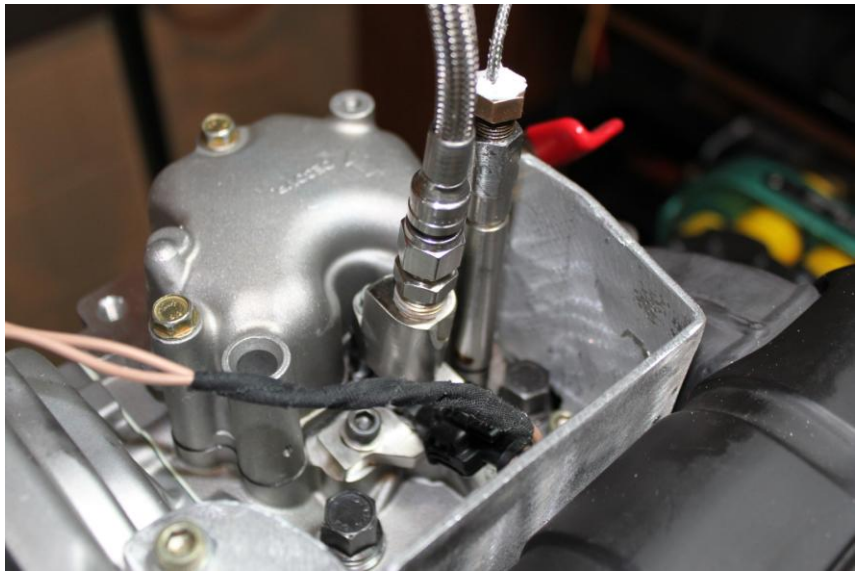


Experimental Setup: Engine

- A year ago …



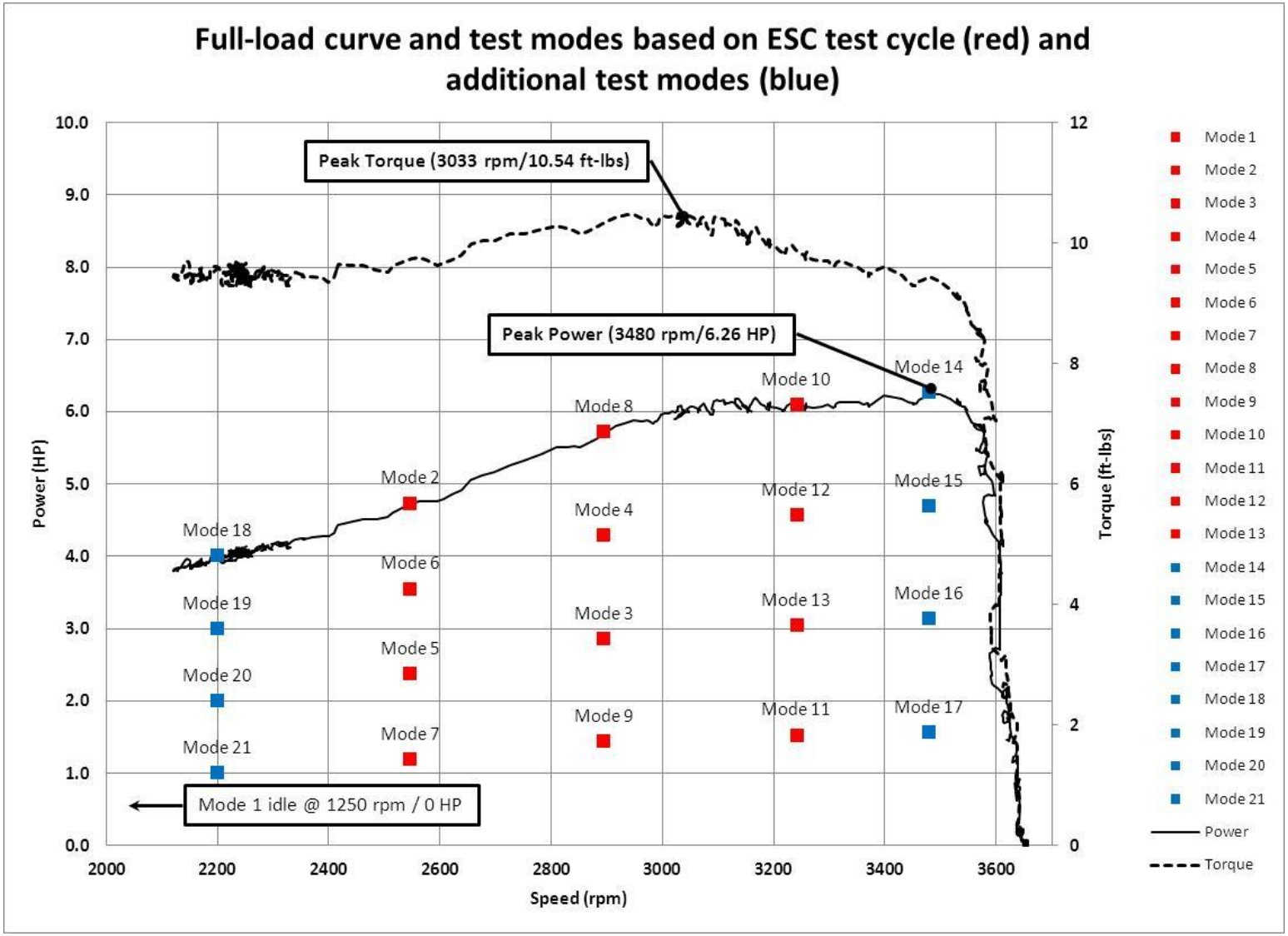
- Today…



Experimental Setup: Injection System

- Electronically controlled common rail direct fuel injection
  - Multiple Injections per combustion cycle
- Bosch fuel injector:
  - Modified gasoline direct injection fuel injector
  - All wetted parts are made from stainless steel
  - Injection pressures of up to 200 bar
- Rail pump:
  - External pump
  - High pressure, air-operated piston pump
- Engine Control Unit
  - Hardware: National Instruments CompactRIO system
  - Injector driver: Iowa State University
  - Software: Iowa State University
- Emissions Analytics
  - Horiba Mexa 7100DEGR (CO_2, CO, O_2, HC)
  - Horiba 1170NX (NO_x, NH_3)
  - AVL Variable Sampling Smoke Meter (PM)

Test Results: Baseline



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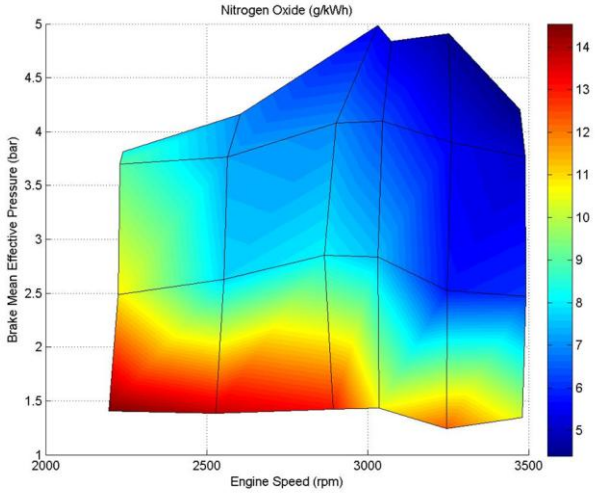

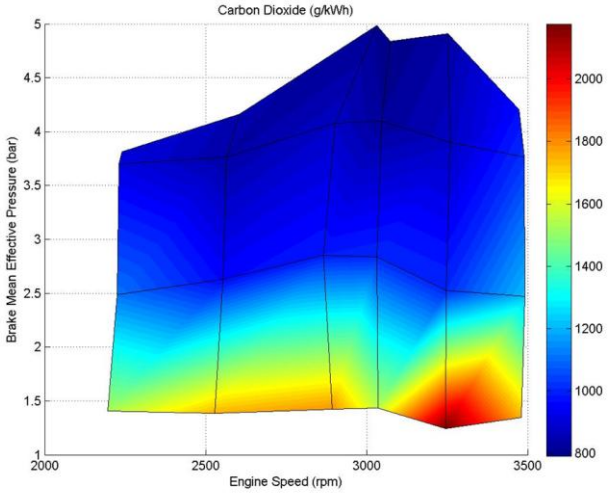

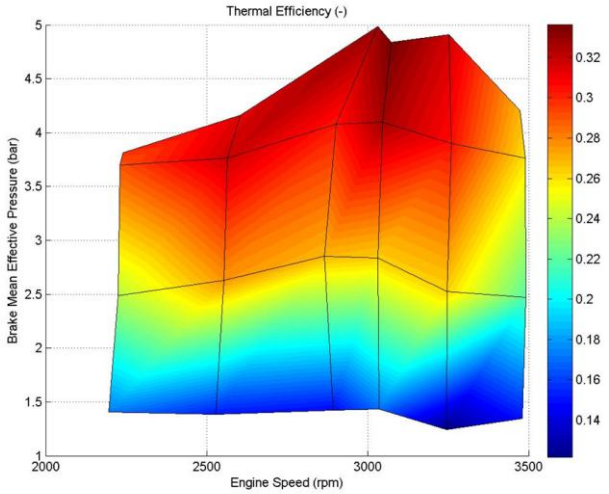

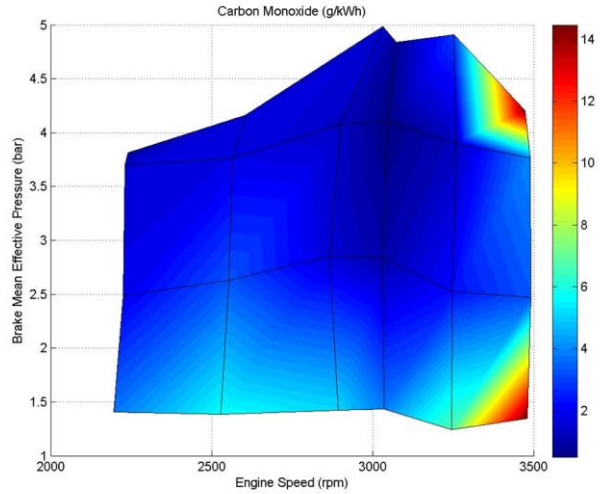

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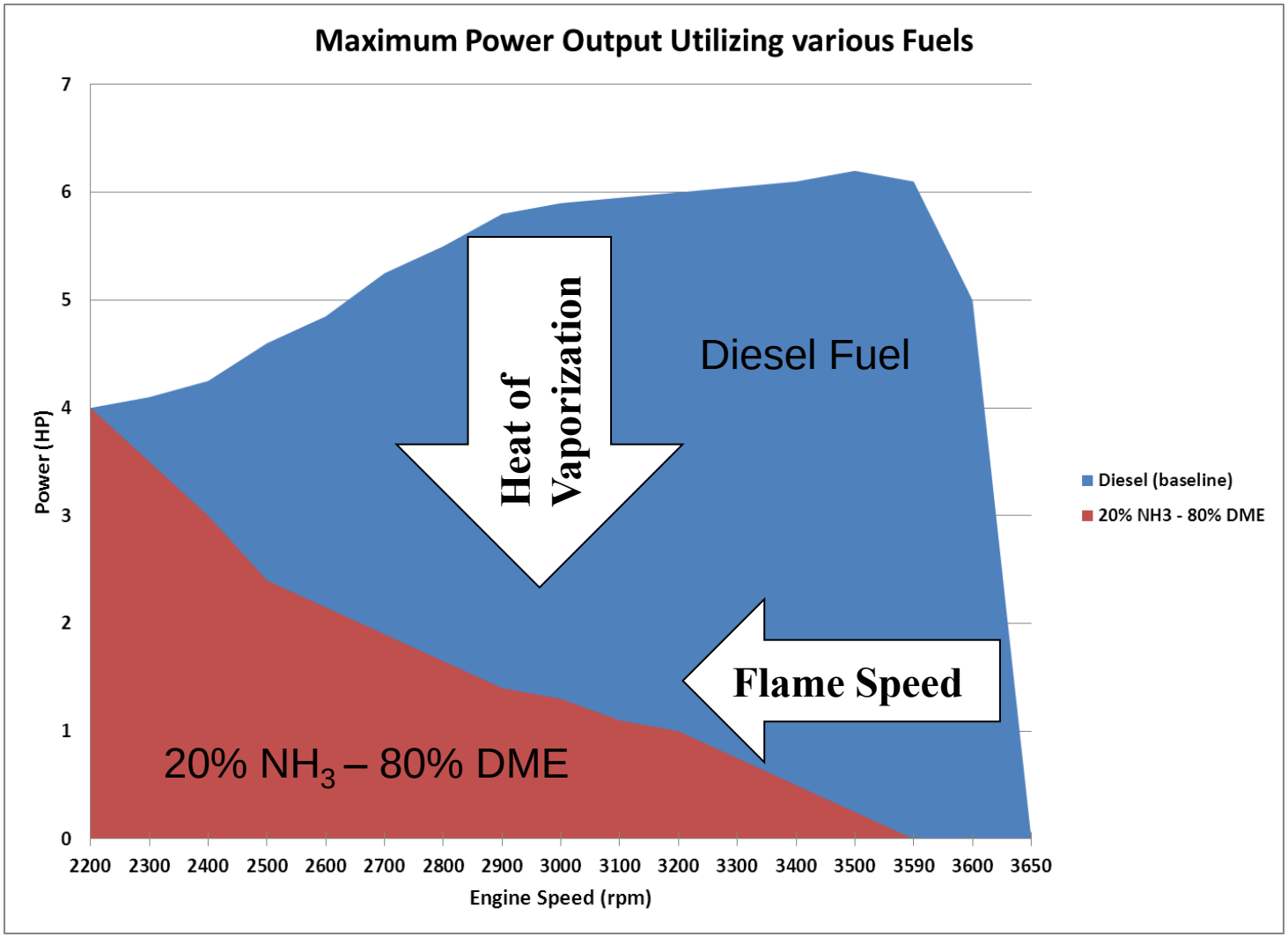

Experimental Setup: Next Steps

- Challenges:
  - Reduce heat loss to vaporization of fuel ⇨ multiple injections
  - Increase flame speed ⇨ increase combustion temperature ⇨ pre-heat intake air
  - Mixing of fuel and air ⇨ new injectors with improved spray pattern

- Targets:
  - Near zero ammonia concentration in exhaust (10 ppm or less)
  - Thermal efficiency comparable to conventional diesel engine (≥ 40%)
  - Low NO_x emissions (≤7.5 g/kWh – Tier 4)
  - High ammonia content in fuel mixture (≥ 90%)
  - Useful engine map comparable to that of base engine

- Thank you for your attention !

  - Questions?

  - Contact Information:

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