Performance of a Compression-Ignition Engine Using Direct-Injection of Liquid Ammonia/DME Mixture

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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)
  - Ammonia flame temperature is lower than diesel flame T
  - Ammonia emissions can be harmful
  - Potential high NOx emissions due to fuel-bound nitrogen
  - Gas phase at atmospheric pressure; Erosive to some materials
  - Low energy content (~40% of that of diesel fuel per unit mass)

Thermodynamics/Chemistry

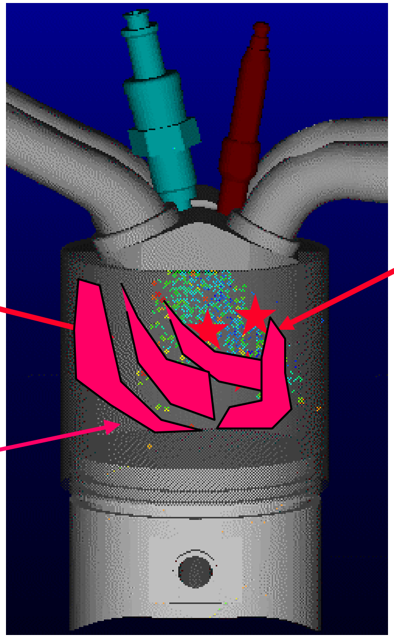
- Stoichiometric chemical reaction

$$NH_3 + 0.75 \cdot (O_2 + 3.76 \cdot N_2) \rightarrow 1.5 \cdot H_2O + 3.32 \cdot N_2$$

Fuel	Molecule	Boiling Point (°C)	$(Air/Fuel)_s$	Latent Heat (kJ/kg)	Energy Content (MJ/kg-fuel)	Energy Content (MJ/kg-stoichiometric mixture)
Methanol	CH_3OH	64.7	6.435	1203	20	2.6900
Ethanol	C_2H_5OH	78.4	8.953	850	26.9	2.7027
Gasoline	C_7H_{17}	---	15.291	310	44	2.5781
Diesel	$C_{14.4}H_{24.9}$	---	14.3217	230	42.38	2.7660
Ammonia	NH_3	**–33.5**	**6.0456**	**1371**	**18.6103**	**2.6414**

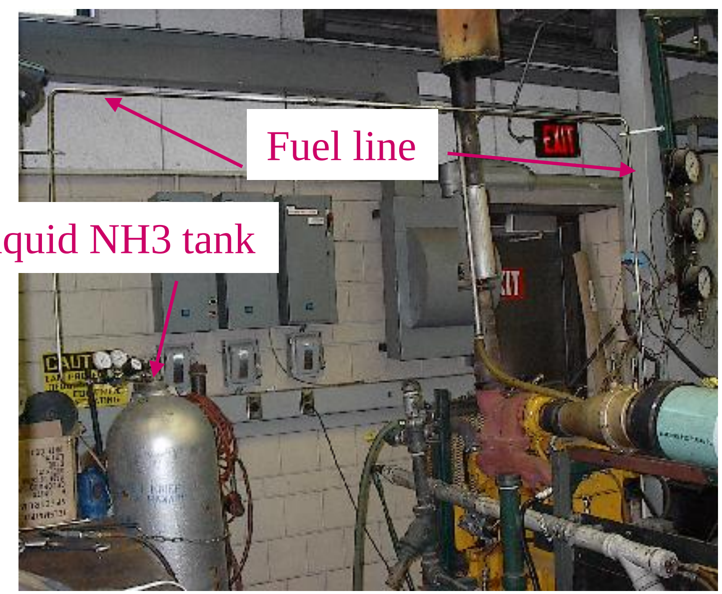
Approach #1

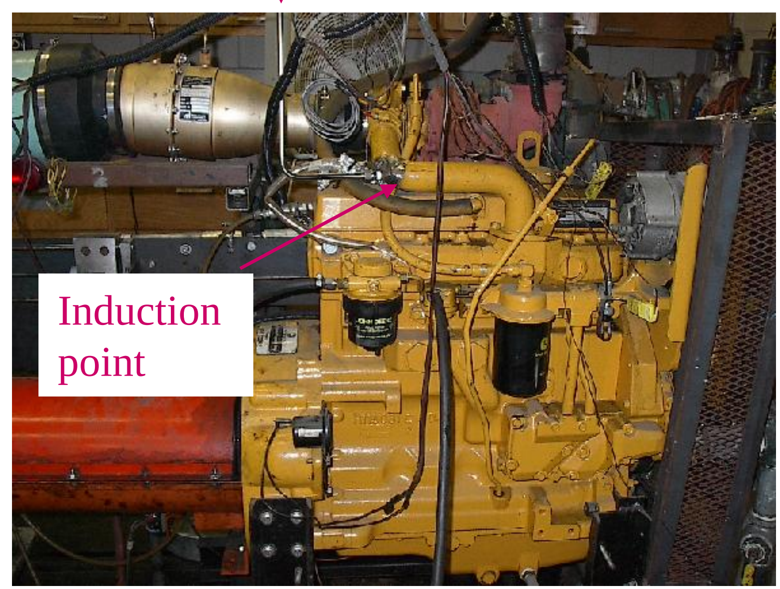
- Introduce ammonia to the intake manifold
- Create premixed ammonia/air mixture in the cylinder
- Inject diesel fuel to initiate combustion
  - Without modifying the existing injection system



Engine Setup

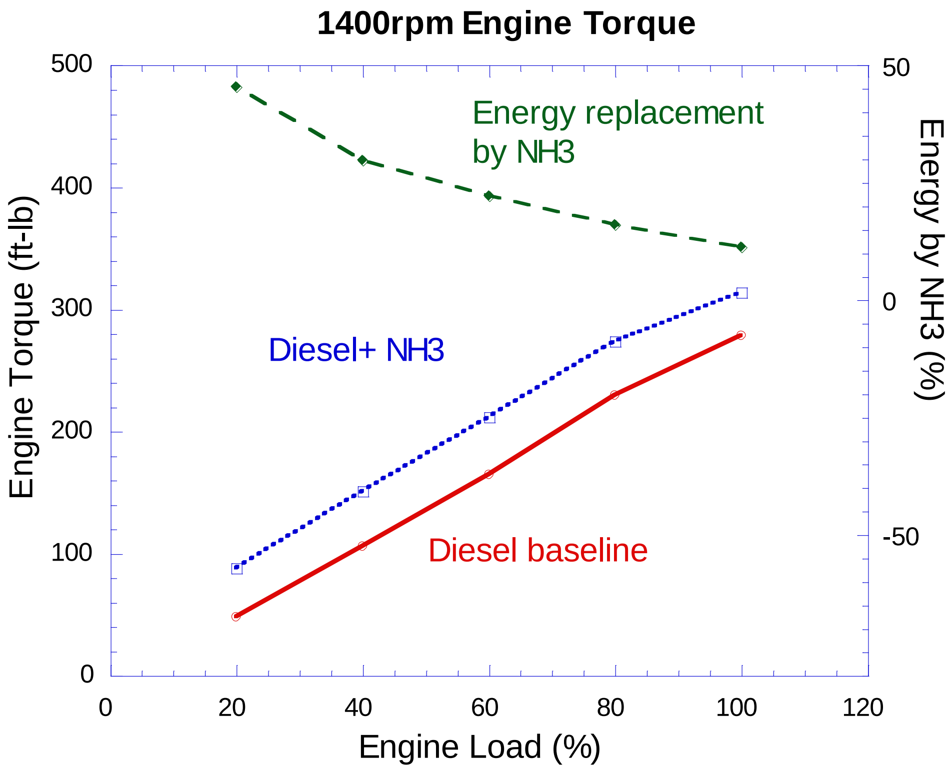
- John Deere (4 cylinder, 4.5 liter)
  - Operated at various load and speed conditions
  - Vapor ammonia introduced into the intake duct – after turbo, before manifold

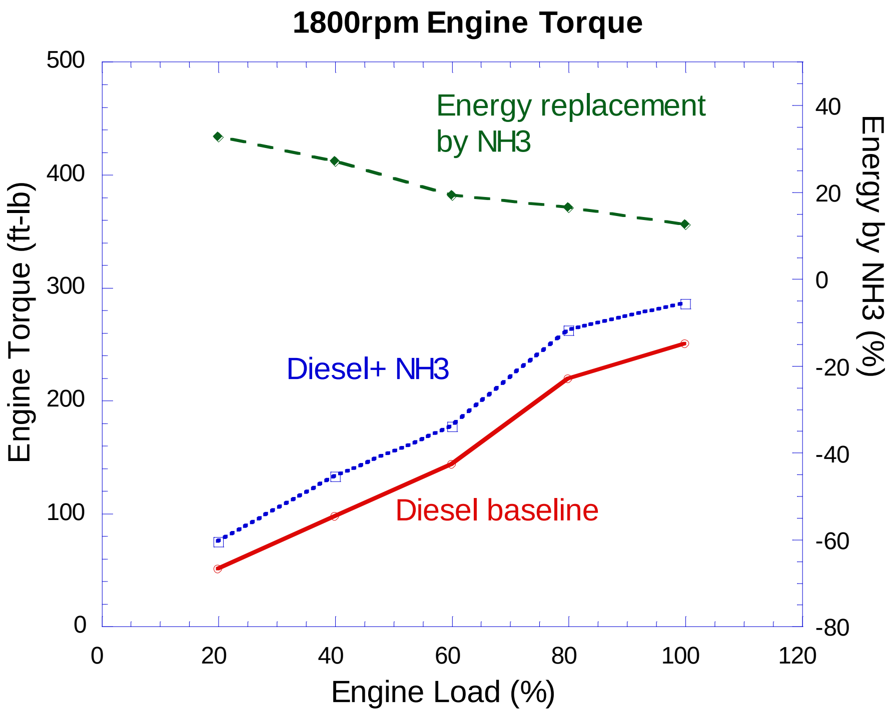




Test Results – Constant NH_3 Flow Rate

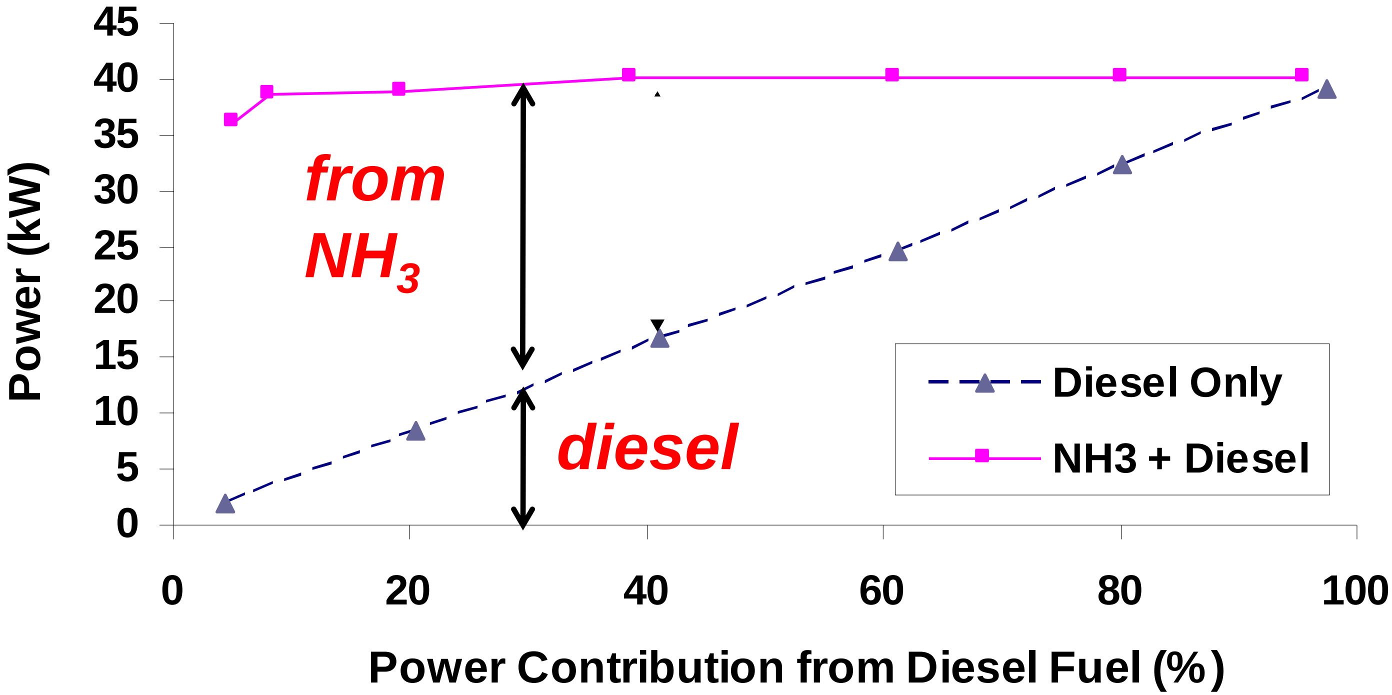
- Engine torque increases suddenly once ammonia is inducted





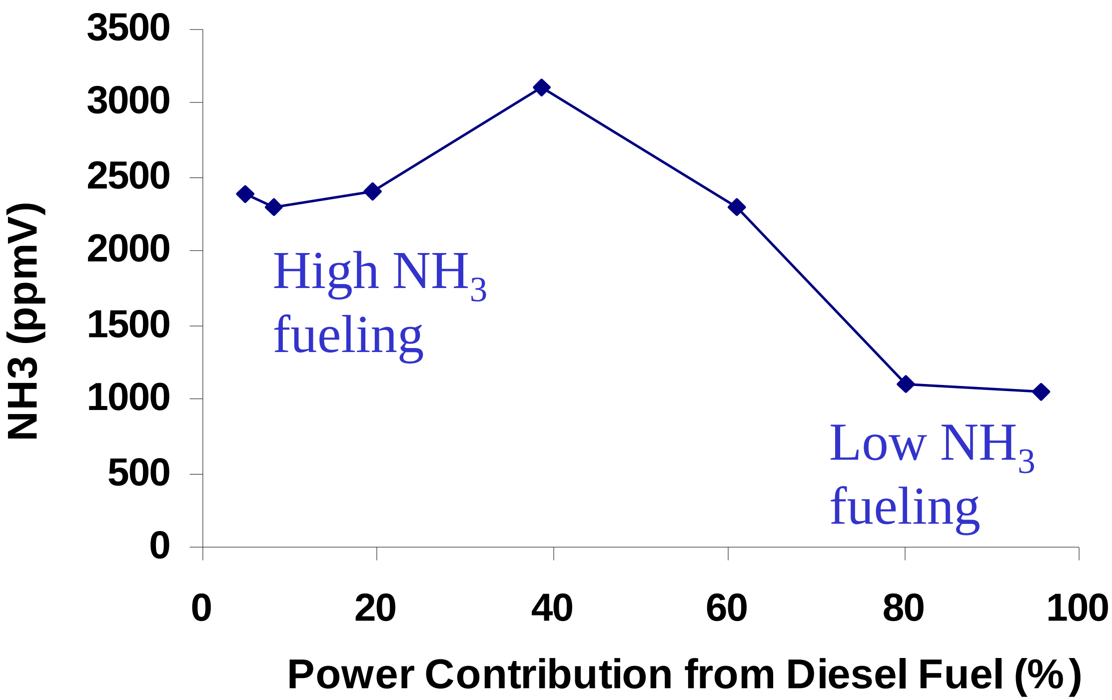
Test Results – Constant Torque

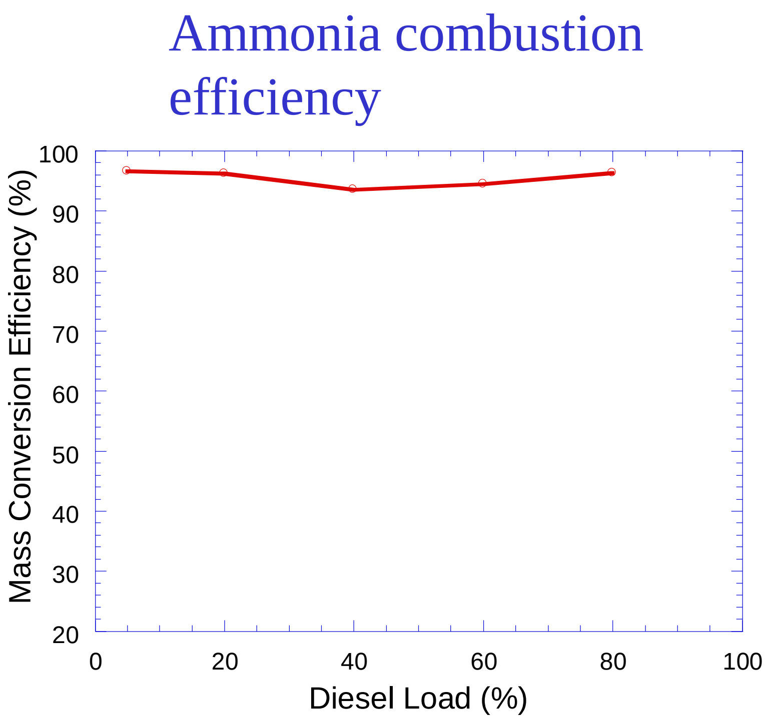
- Fixed at specific diesel fueling, adjusted NH3 flow rate to maintain constant torque
  - Can achieve 5% diesel / 95% NH_3 energy ratio



NH_3 Exhaust Concentrations

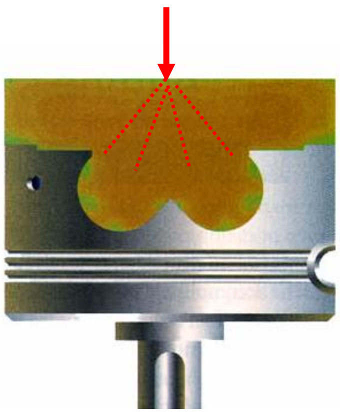
- Concentrations vary depending on NH_3 fueling rate
- Further study is required to reduce NH_3 emissions.





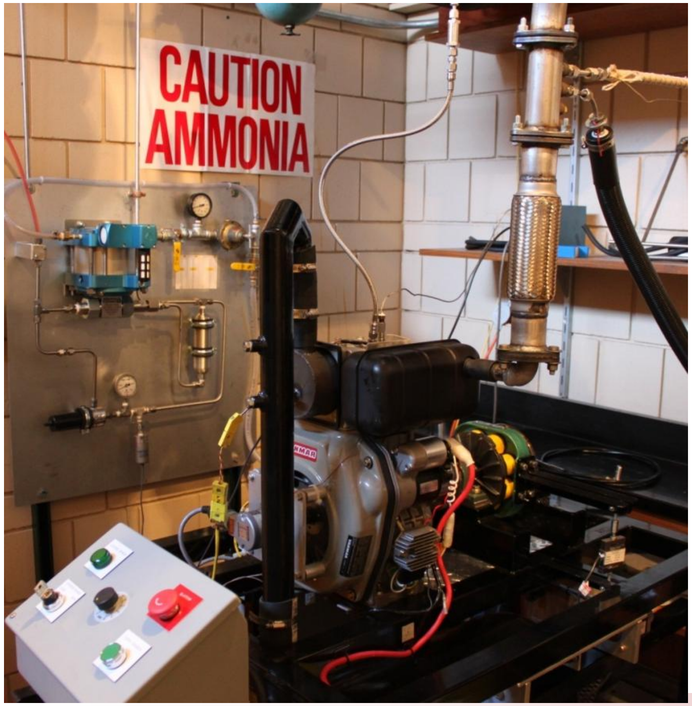
Approach #2

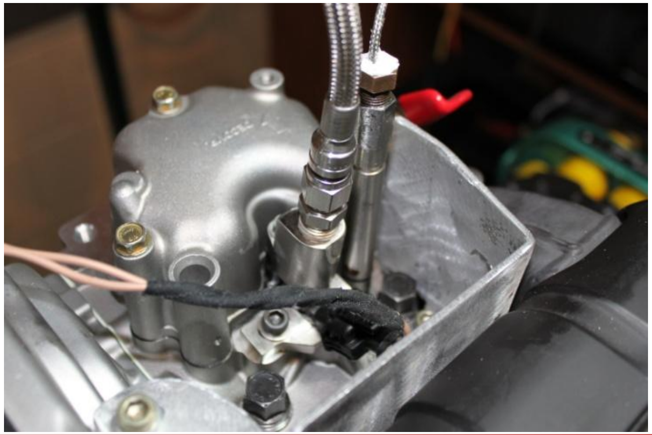
- Use direct liquid fuel injection
  - Confine combustion mixture near the center
  - To reduce exhaust ammonia emissions
- Ignition source – dimethyl ether (CH_3-O-CH_3)
  - Mixture of DME and NH3
  - Fuel mixing and storage at high pressure
  - New fuel injection system – without fuel return
    - Injection pump, injector, electronic control



Engine Setup

- Yanmar diesel engine (L70V, 320 c.c.)
  - Rated power at 6.26 hp at 3480 rpm
- Develop new fuel injection and engine control systems
  - Bosch GDI type injector (up to 200 bar injection pressure)





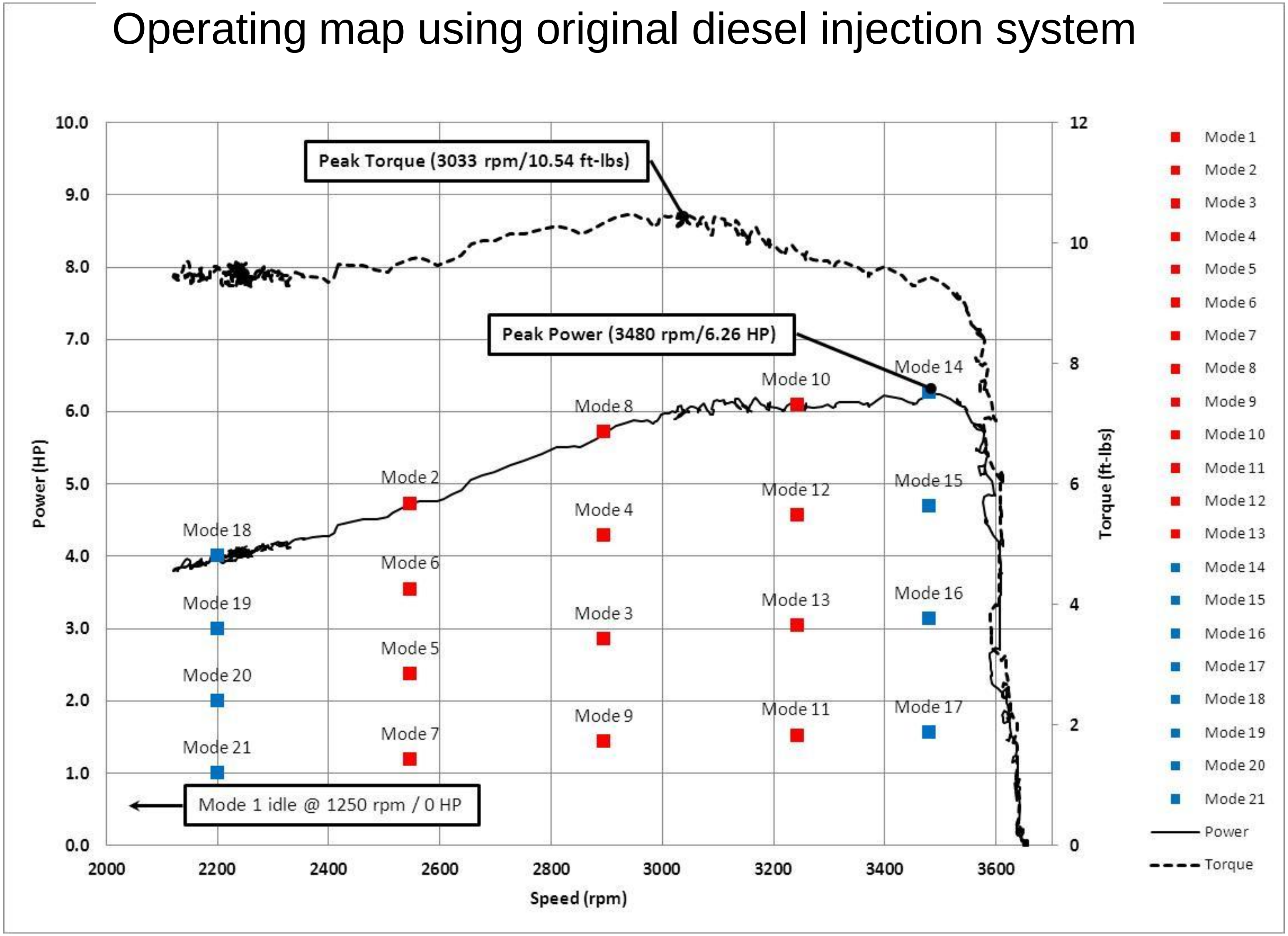
Setup

- Mixing and storage of ammonia/DME at high pressure
- Exhaust emissions measurements
  - Horiba MEXA-7100DEGR (CO_2, CO, O_2, HC)
  - Horiba 1170NX (NO_x, NH_3)
  - AVL Smoke Meter (PM)

Emissions analyzers

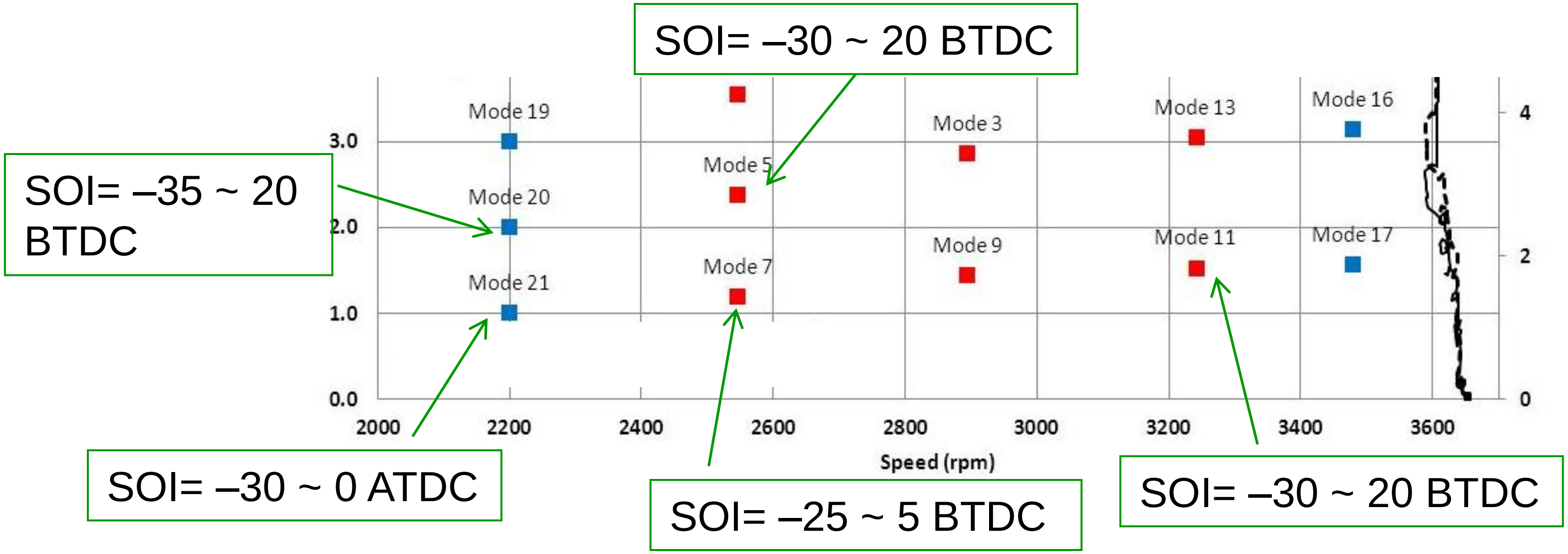
Fuel mixing system

Operating Conditions



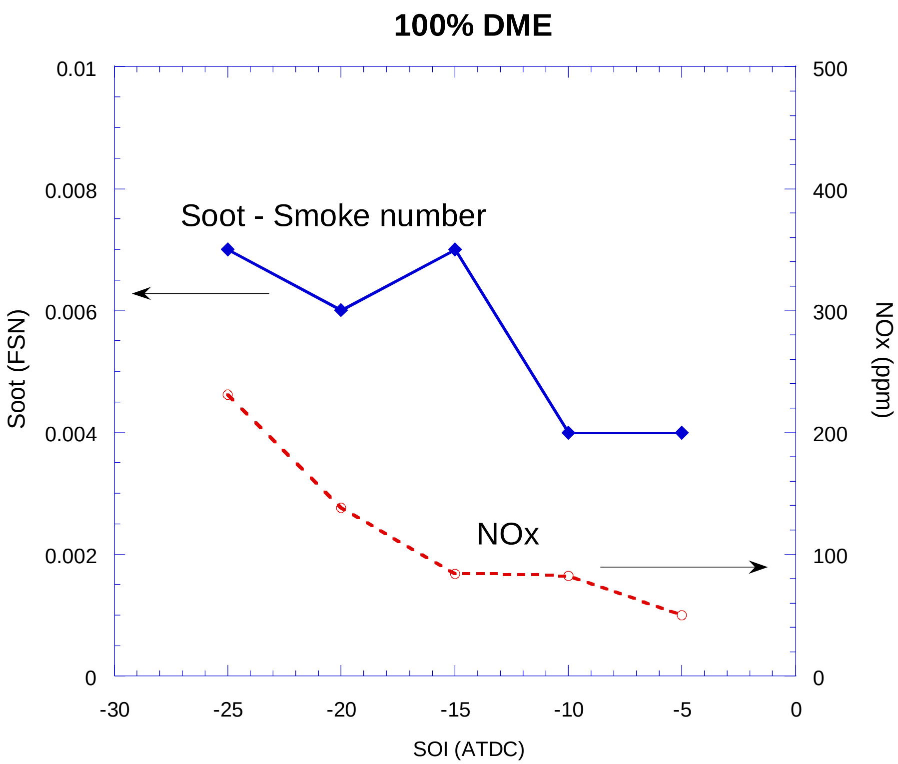
Test Results

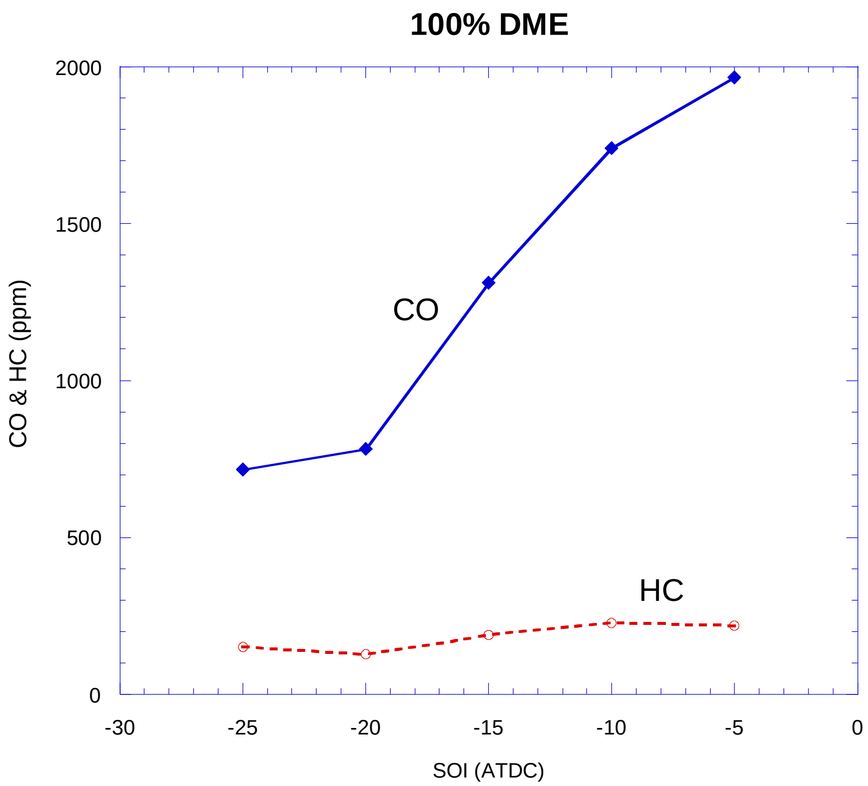
- Baseline operation using 100% DME
  - Explore operating range before using NH3/DME mixture
  - For each operating point, various start-of-injection timings were tested
  - Provide flexibility for future optimization



100% DME

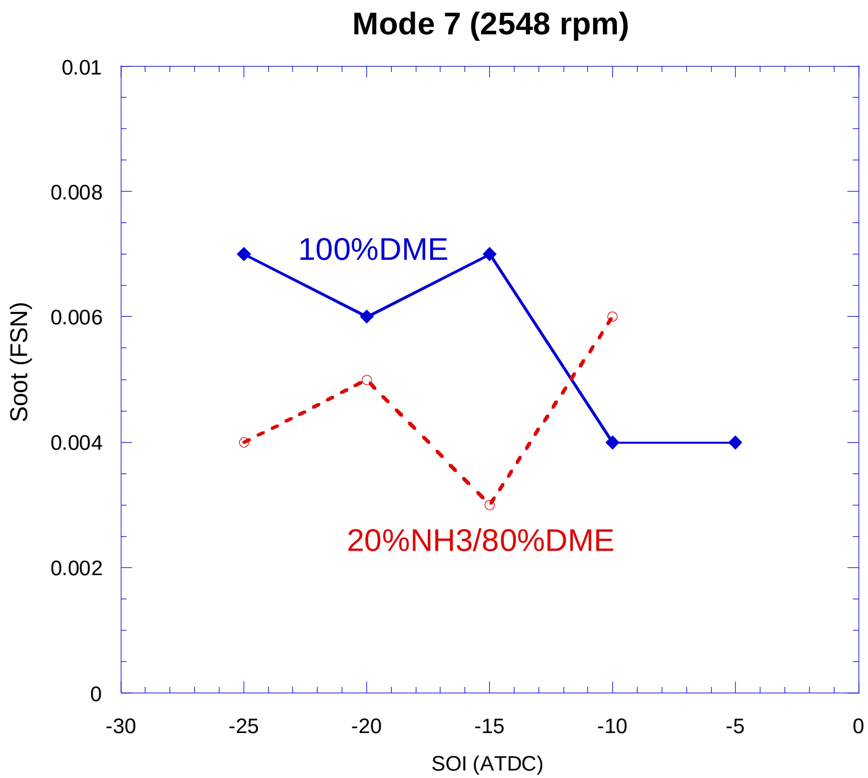
- Mode 7 (2548 rpm) emissions

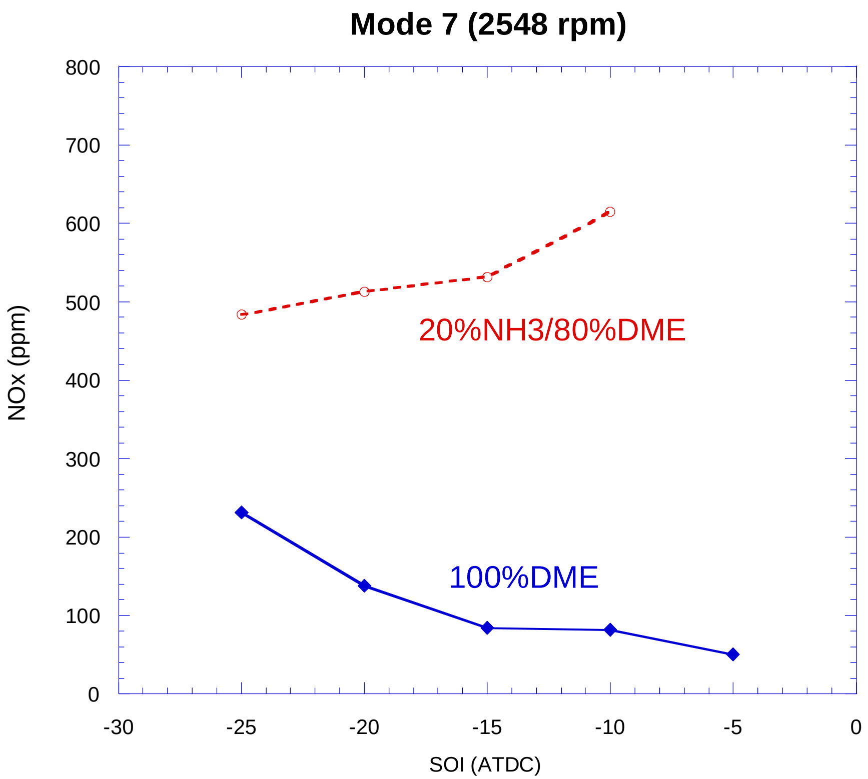




Effects of Ammonia Combustion (Mode 7)

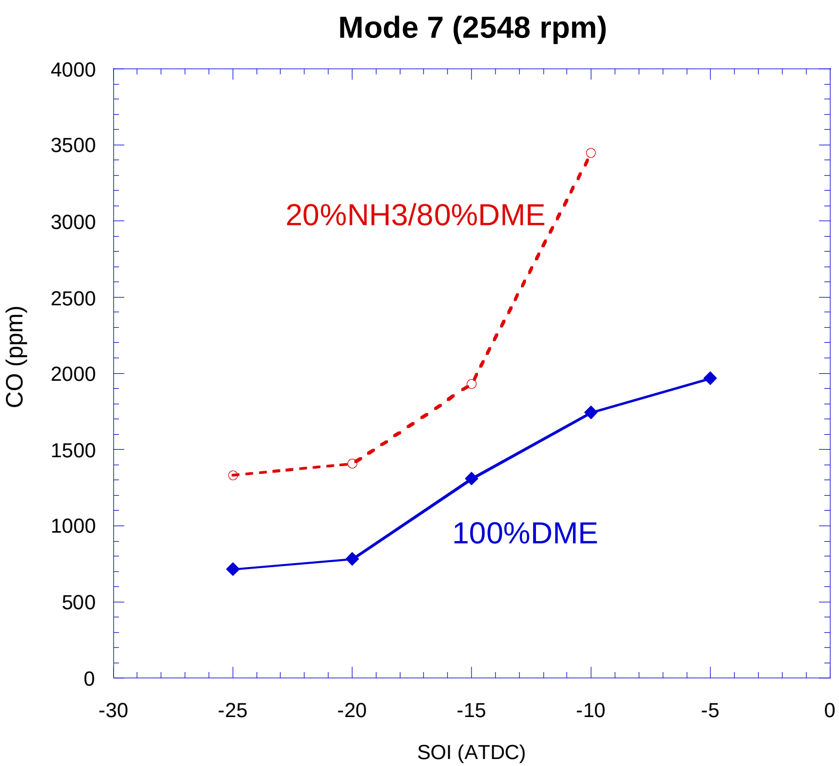
- 100%DME vs. 20%NH3/80%DME
  - Soot remains at low level
  - NOx increases due to fuel-bound nitrogen

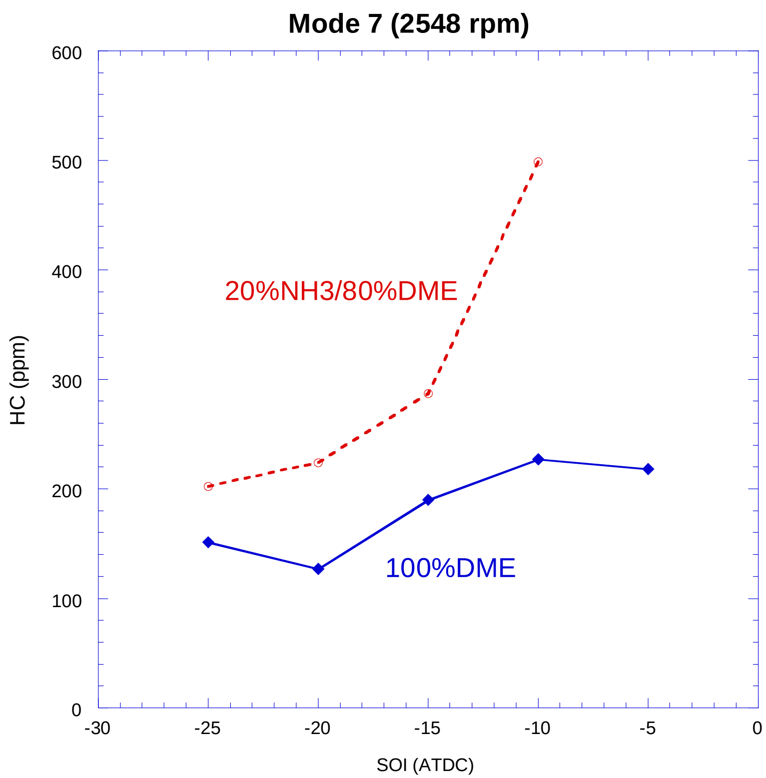




Effects of Ammonia Combustion (Mode 7)

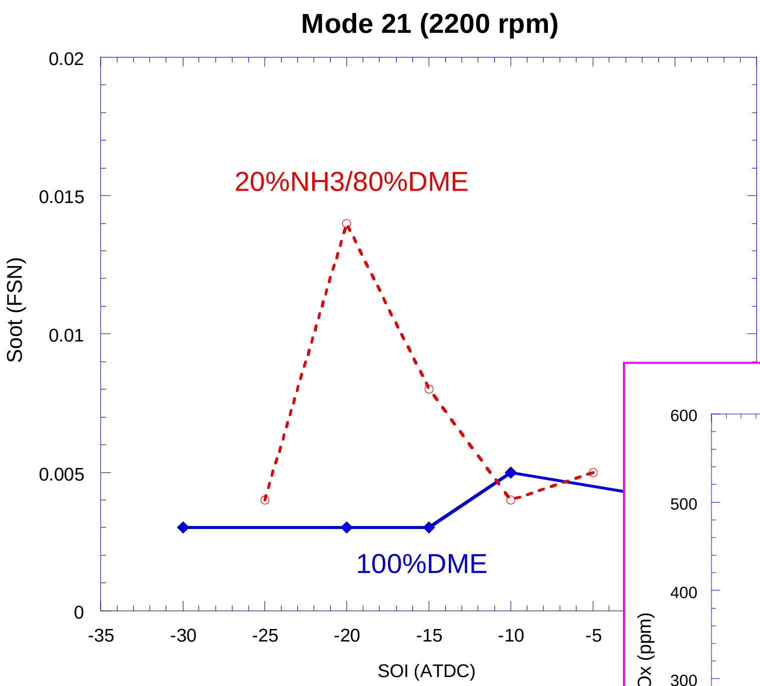
- 100%DME vs. 20%NH3/80%DME
  - Lower combustion temperature of ammonia causes more CO and HC emissions
  - Implication to fuel efficiency

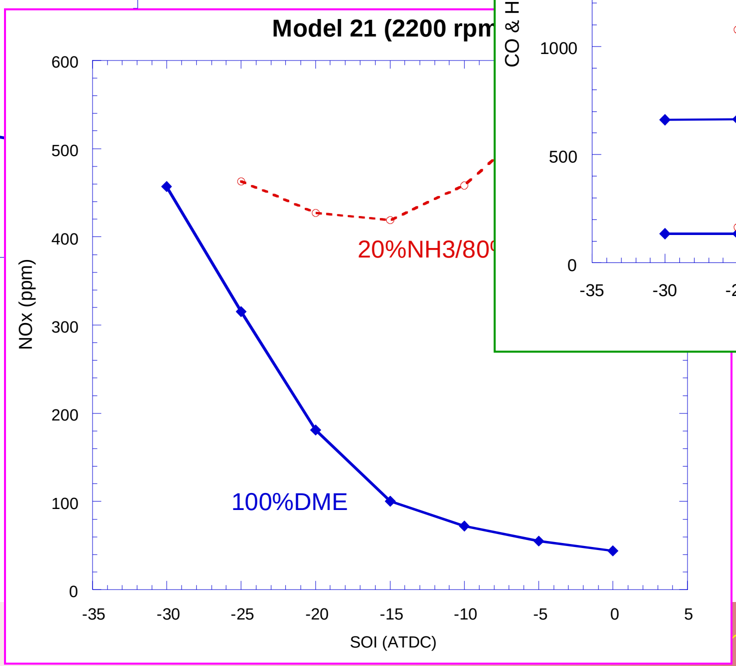


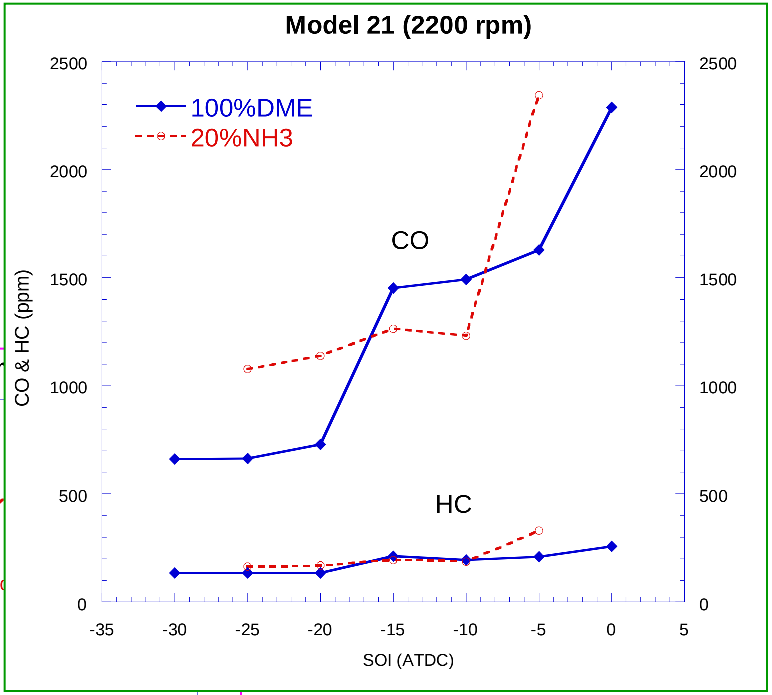


Effects of Ammonia Combustion (Mode 21)

- Comparable combustion and fuel efficiency at this lower speed

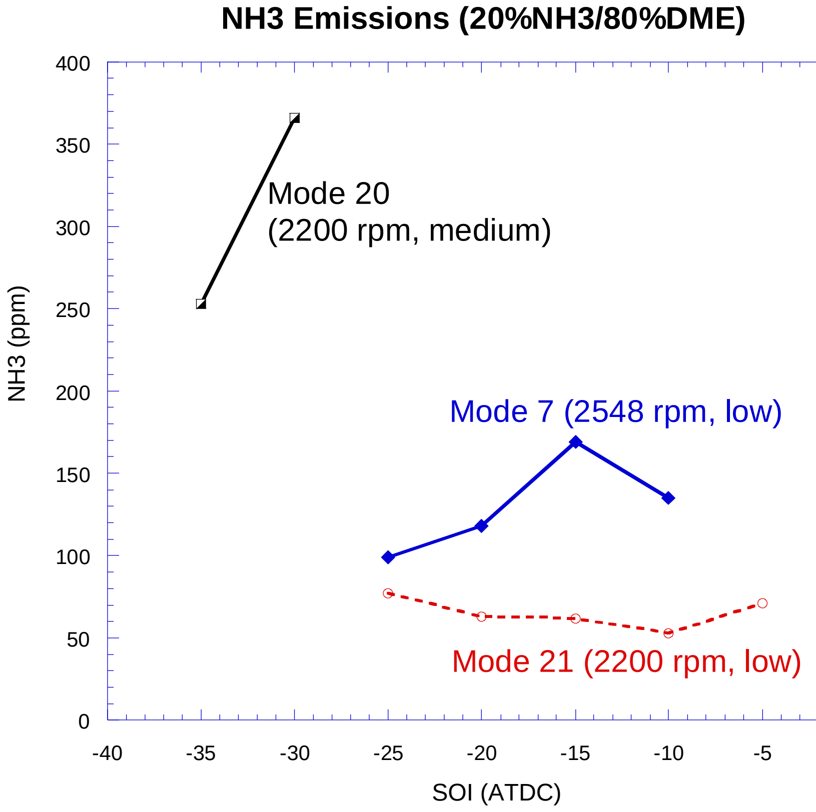






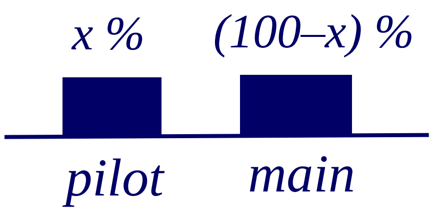
Effects of Ammonia Combustion

- Exhaust ammonia emissions much lower than Approach#1
- Direct injection strategy benefits exhaust ammonia emissions



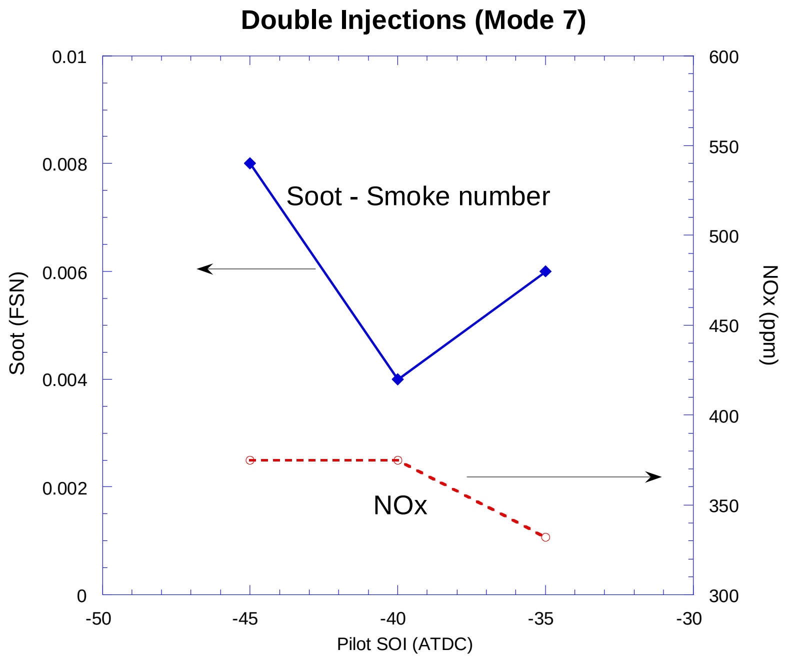
Alternate Injection Strategy

- To extend the operating range
- Proposed strategies
  - Double fuel injections
    - Offer flexibilities in fuel delivery
    - Used in industry for emissions and noise reduction
  - New fuel injector
    - Original: single hole
    - Alternate: eight holes – help with air utilization



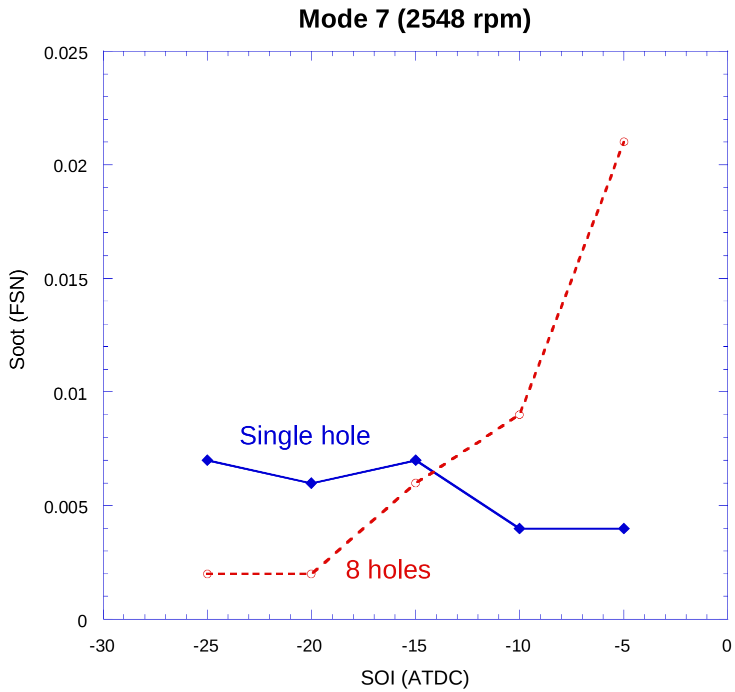
Double Injection, 100% DME

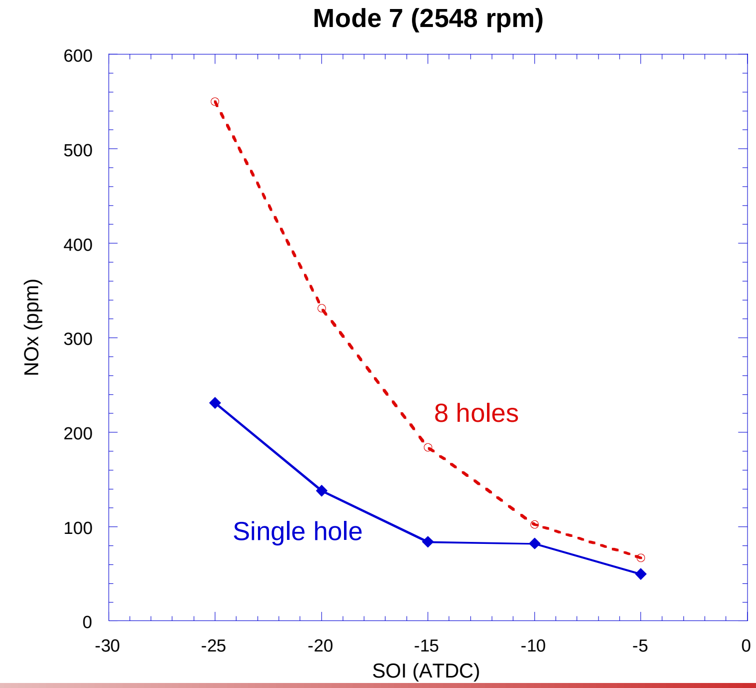
- Current system modified for using double injections
  - Engine operations possible using double injections
  - Comparable fuel efficiency and emissions
  - Results based on Mode 7 (2548 rpm)
    - Pilot SOI= –45 ~ –35 ATDC
    - Pilot quantity=30% of total fuel
    - Main SOI= –10 ATDC
- Exploring other conditions
  - Varying the three injection variables
  - Other operating points



Multi-Hole Injector

- Change from single hole to 8 holes
  - Higher exhaust NOx – may imply higher combustion temperature to sustain higher load operation
- Exploring combination of using 8-hole injector in combination with double injections





Summary

- Demonstrated ammonia combustion in diesel engines
- Port induction of ammonia coupled with direct-injection diesel fuel
  - Exhaust ammonia level at “thousands of ppm” under the conditions studied
- Direct injection of ammonia/DME
  - Exhaust ammonia level at “hundreds of ppm” under the conditions studied
  - Exploring optimal injection strategies for ammonia combustion
- Perspectives – effects of engine size
  - Challenges for small engine: more heat loss, higher engine speed required, lower fuel injection pressure
  - Large engine will favor ammonia combustion