Demonstrate Ammonia Combustion in Diesel Engines

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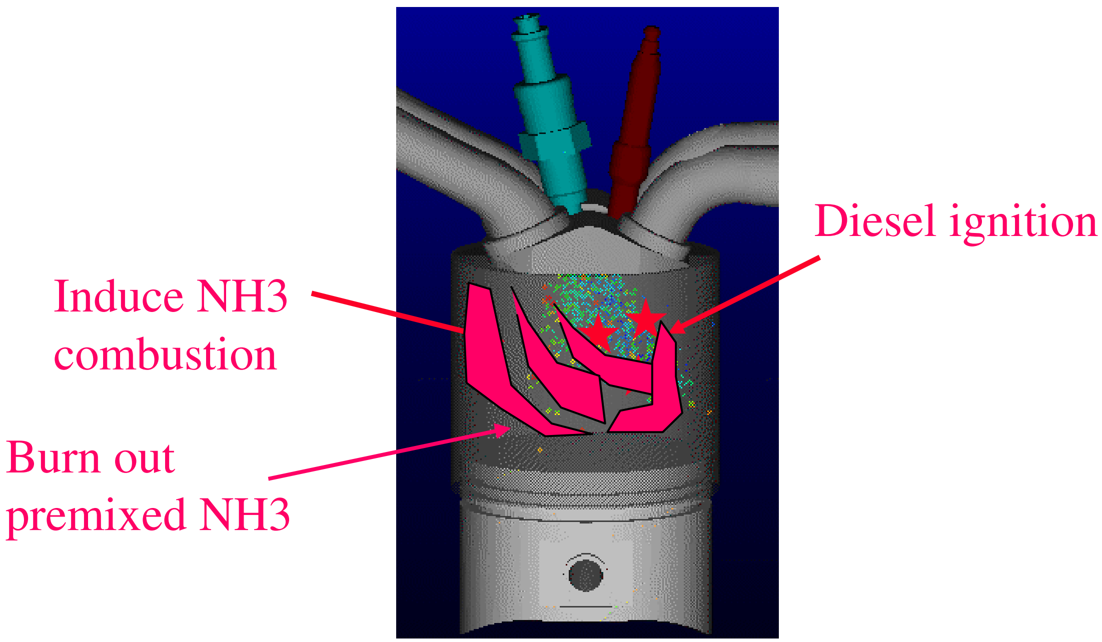
Background

- Motivation
  - Ammonia (NH_3) combustion does not generate CO_2
  - Biorenewable; Hydrogen carrier, key to hydrogen economy, etc.
- Challenges
  - Ammonia is very difficult to ignite
    - Octane number ~ 130
    - Autoignition T ~ 651 ºC (gasoline: 440 ºC; diesel: 225 ºC)
  - Erosive to some materials
  - Fuel induction system modification
  - Less energy content – maximize energy substitution using NH_3
  - Others …..

Approach

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



Presentation Outline

- Ammonia combustion properties and implications
- Chemical kinetics study
- Experimental setup
- Baseline engine performance with diesel fuels
- Engine test using dual fuel – diesel/NH_3
- Emissions results
- Summary

Thermodynamics/Chemistry

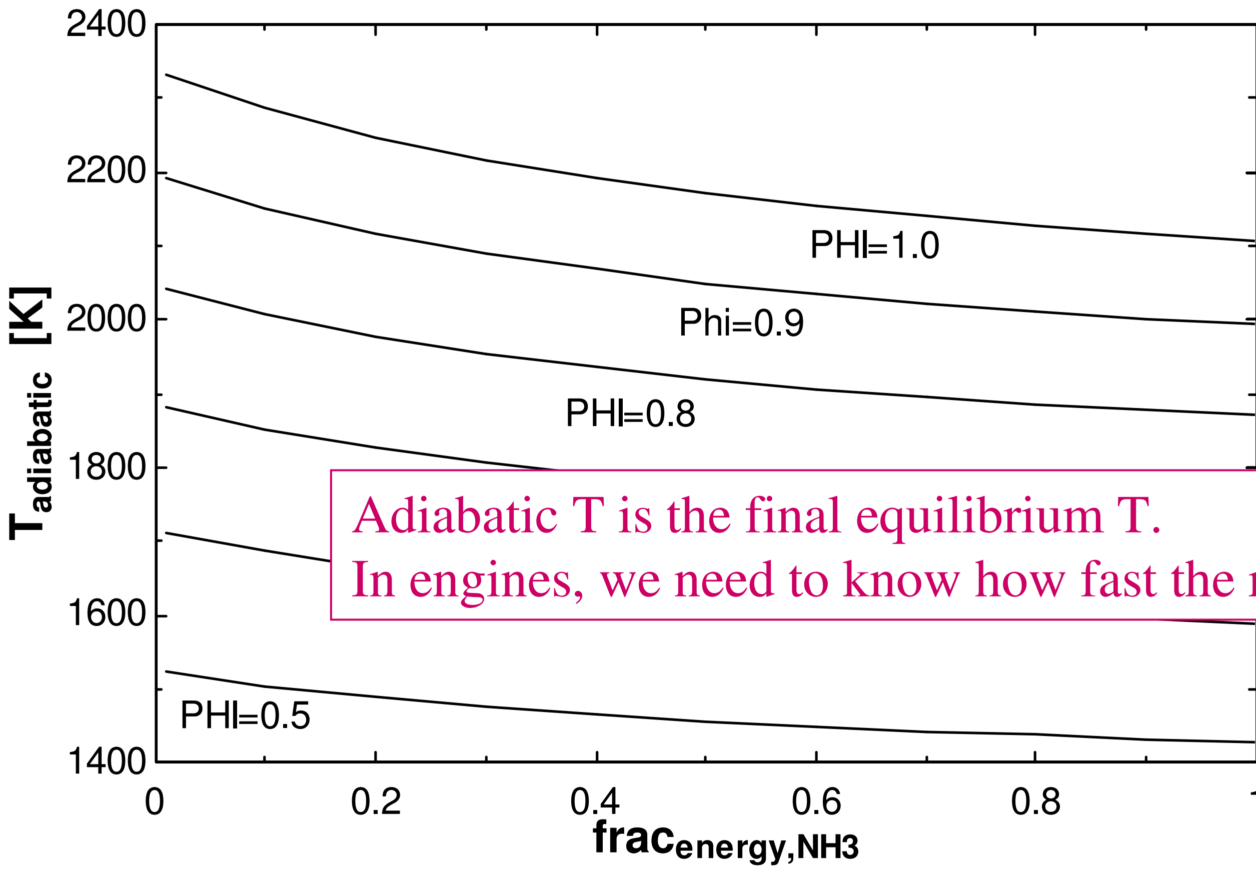
- Stoichiometric chemical reaction

$$NH_3 + 0.75 \cdot (O_2 + 3.76 \cdot N_2) \rightarrow 1.5 \cdot H_2O + 1.91 \cdot N_2$$

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**

Thermo-Chemistry

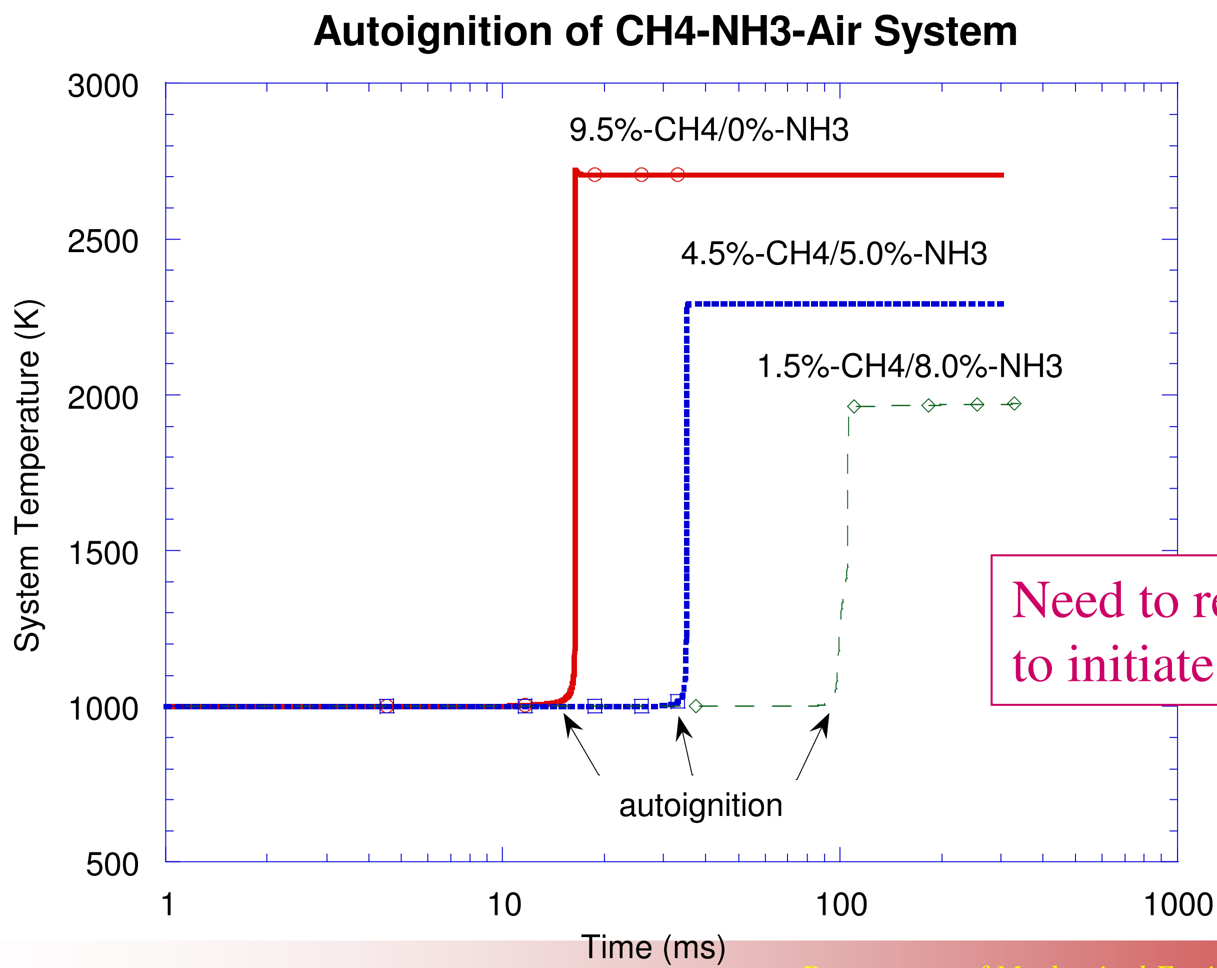
- Adiabatic flame temperature of NH_3/diesel mixture
  - NH_3 energy fraction with different equivalence ratios



Adiabatic T is the final equilibrium T.
In engines, we need to know how fast the reaction goes!

Chemical Kinetics – Methane/Ammonia

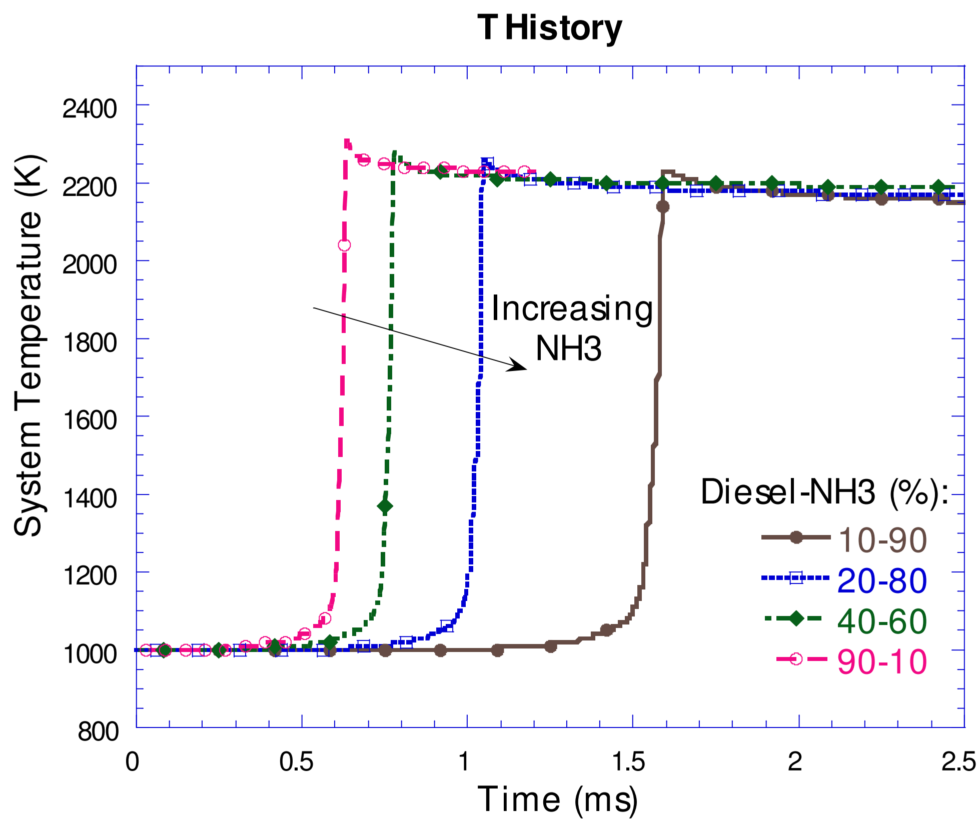
- Ignition delay – important parameter in CI engines
- Replacing HC fuel with NH3 will delay ignition



Need to rely on HC fuel to initiate combustion!

Chemical Kinetics – Diesel/Ammonia

- Ignition delay in a constant-volume chamber
  - Diesel/NH3 system



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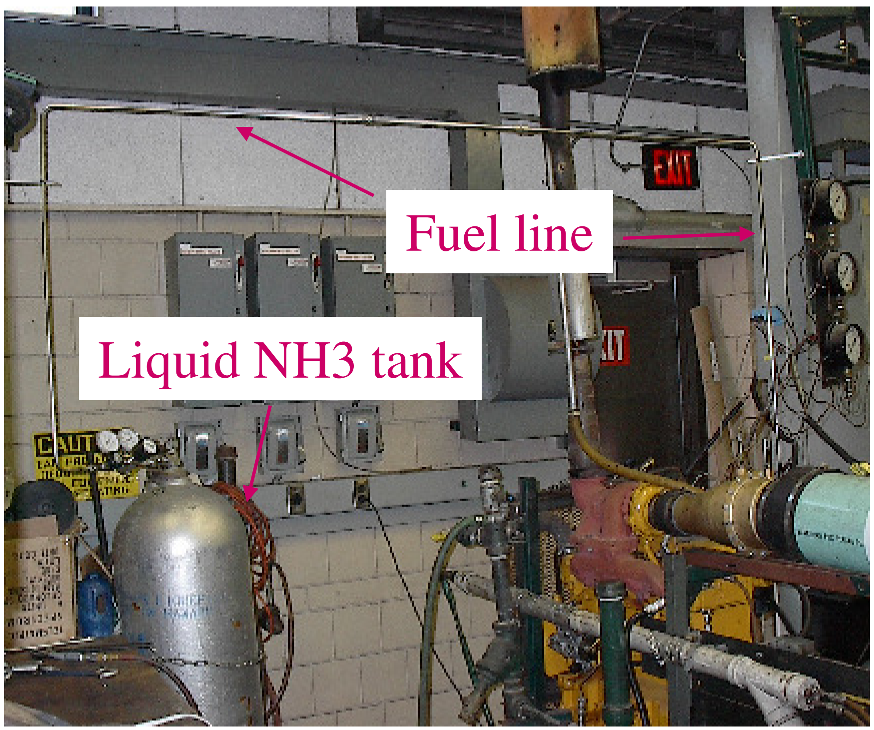
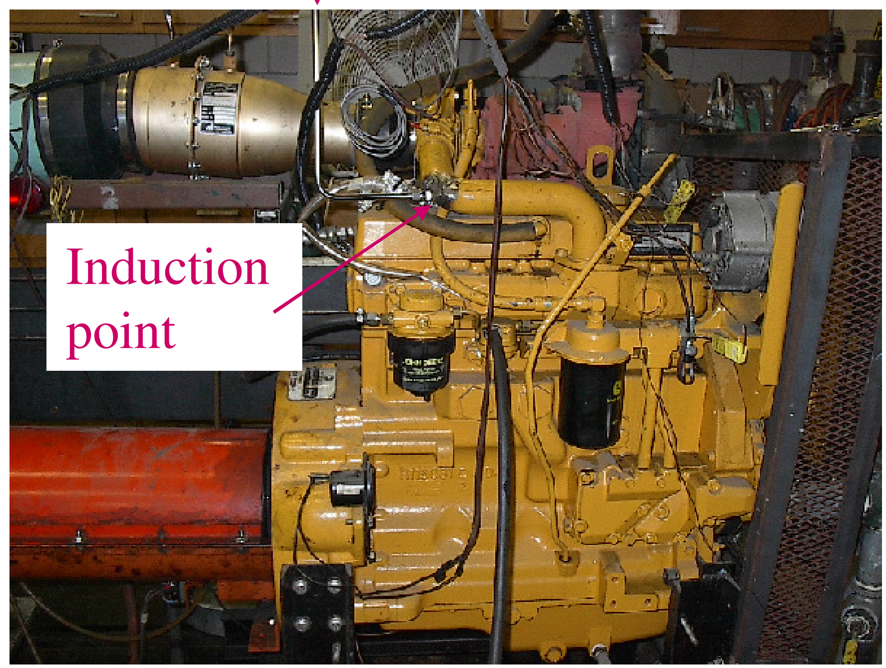
Test Engine

- John Deere 4045 Engine
  - Turbocharged, 4-cylinder, 4.5 liter displacement
  - Popular Deere engine – various tracker & Genset applications
  - Peak torque range – 280 ft-lb at 1400 rpm
- Test conditions
  - Various engine speeds (1000 ~ 1800 rpm)
    - Various engine loads (5% ~ 100%) for each speed
    - Each speed/load point – with and without NH3 induction
  - Test data – torque, BSFC, emissions
  - Only selected data are shown

Ammonia Fueling System

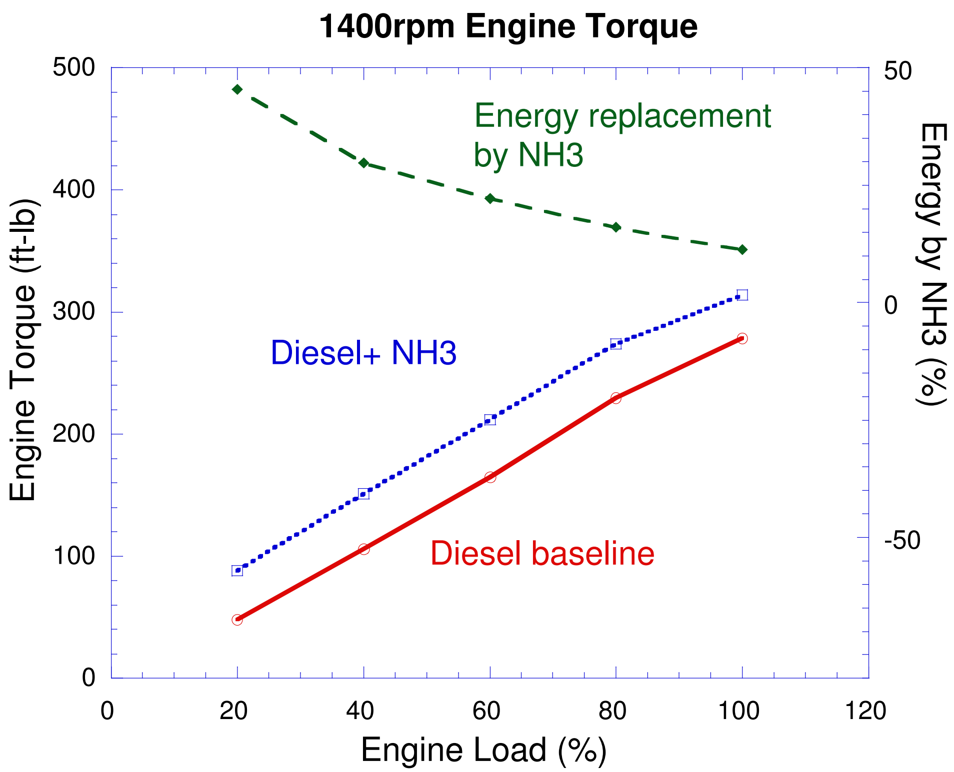
- Fuel system
  - Vapor ammonia introduced into the intake duct – after turbo, before manifold

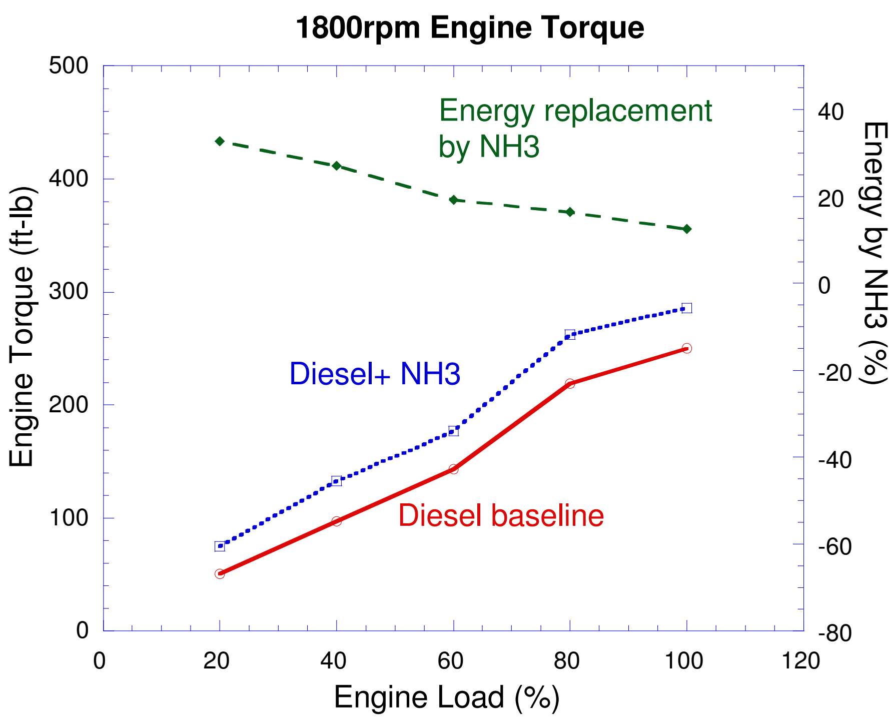




Test Results – Constant NH3 Flow Rate

- Using one ammonia tank and single fuel line





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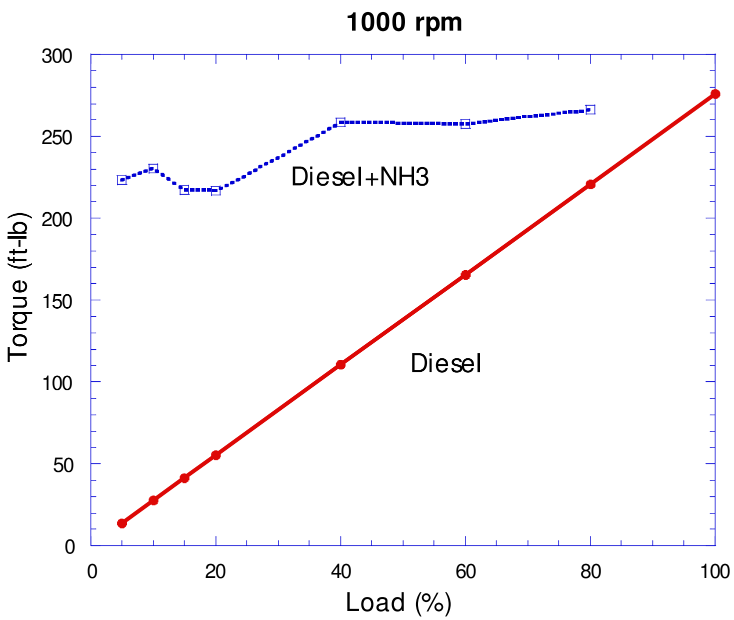
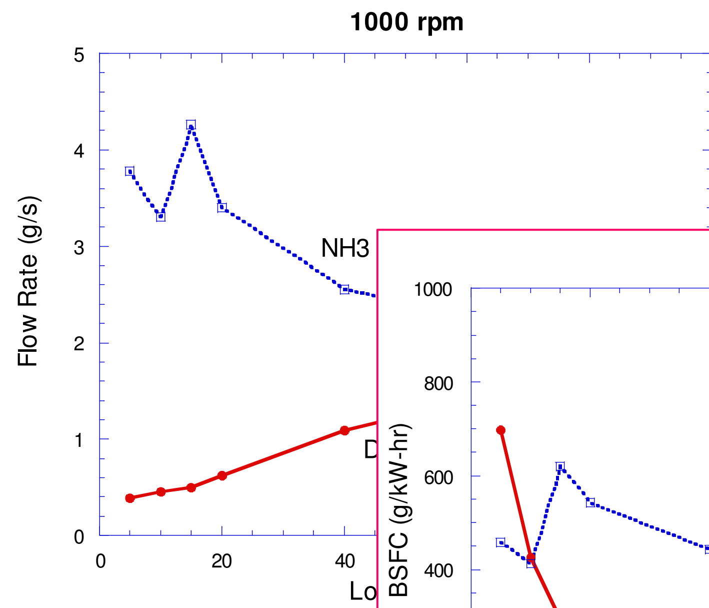
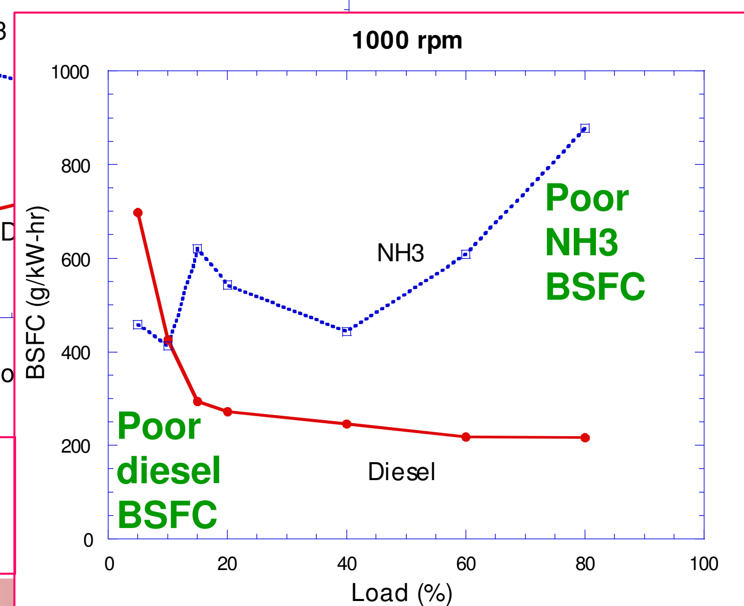
Test Results – Constant Torque

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



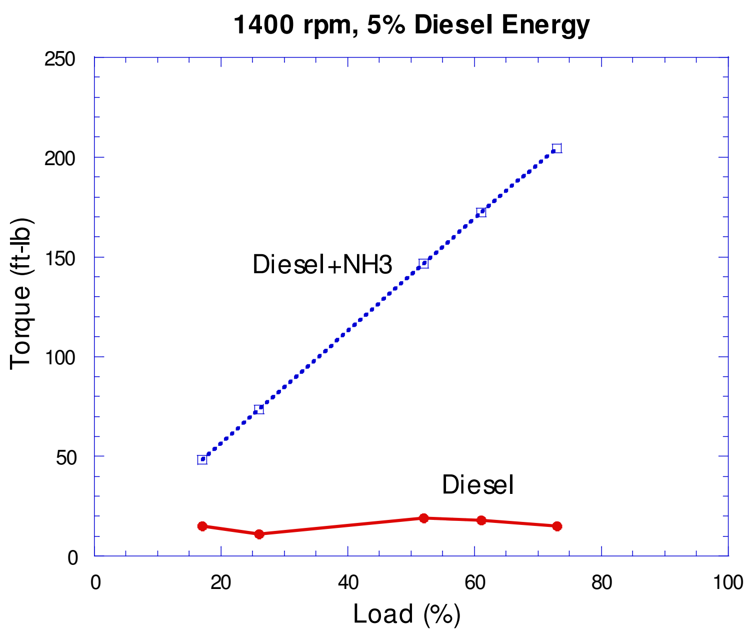


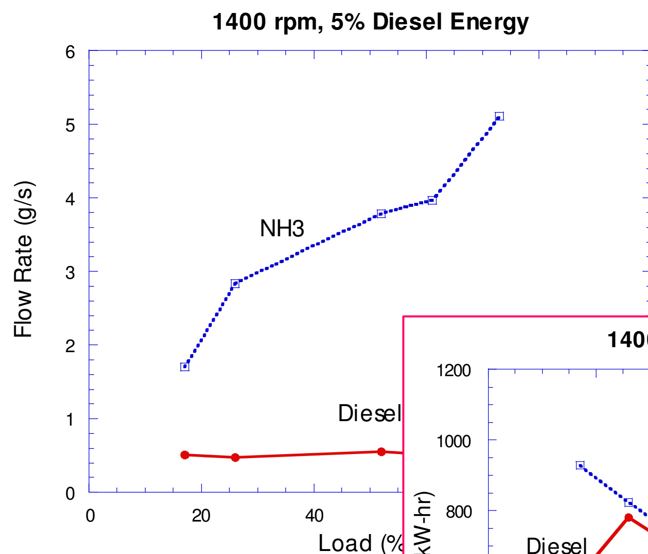


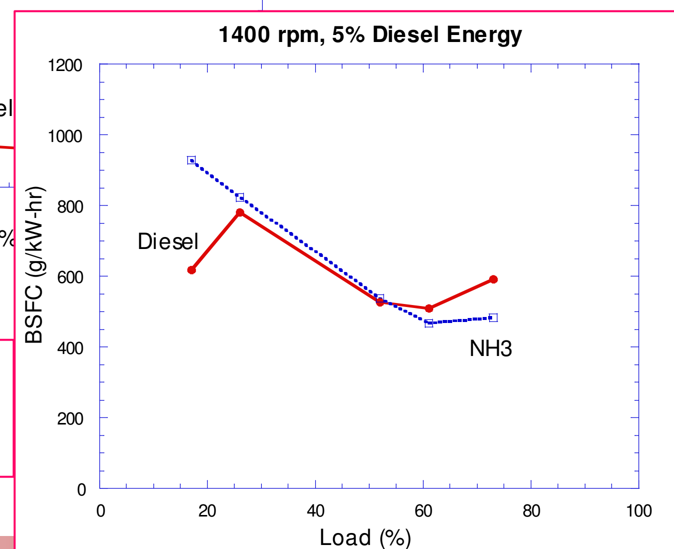
BSFC_diesel & BSFC_NH3 calculated separately based on individual flow rate and torque contribution

Test Results – Variable Torque

- Goal – to achieve maximum energy substitution
  - Diesel fueling was maintained at approximately 5%
  - Adjusted NH3 rate for desirable engine torque





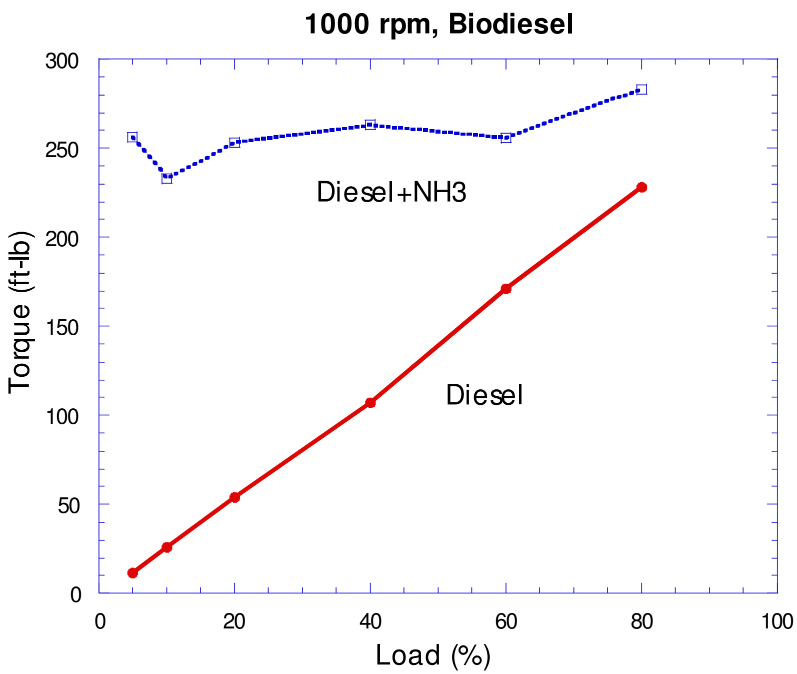


Can achieve high NH3 ratio
but poor fuel economy

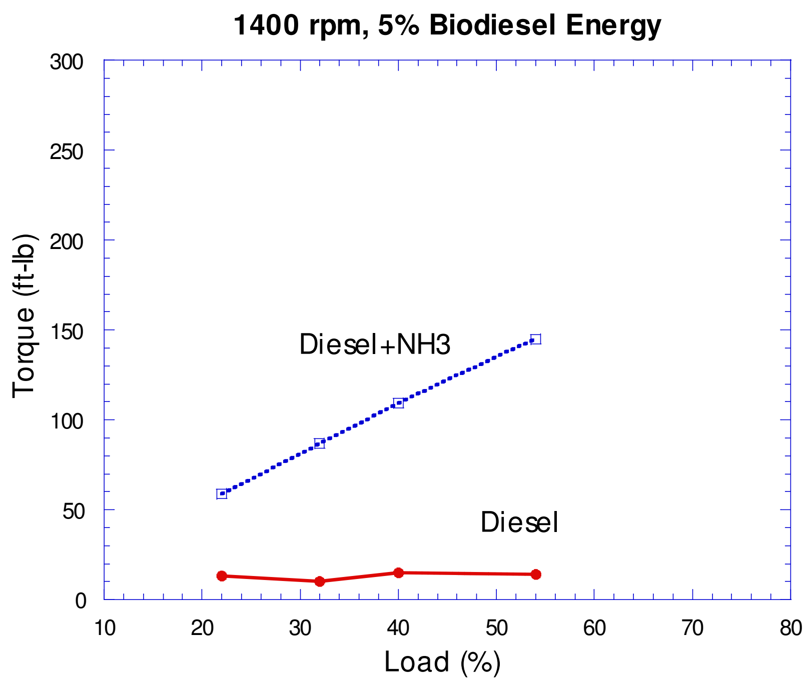
Test Results – Using Biodiesel

- B100 was used
- Can achieve similar results as regular diesel fuel

Constant engine torque

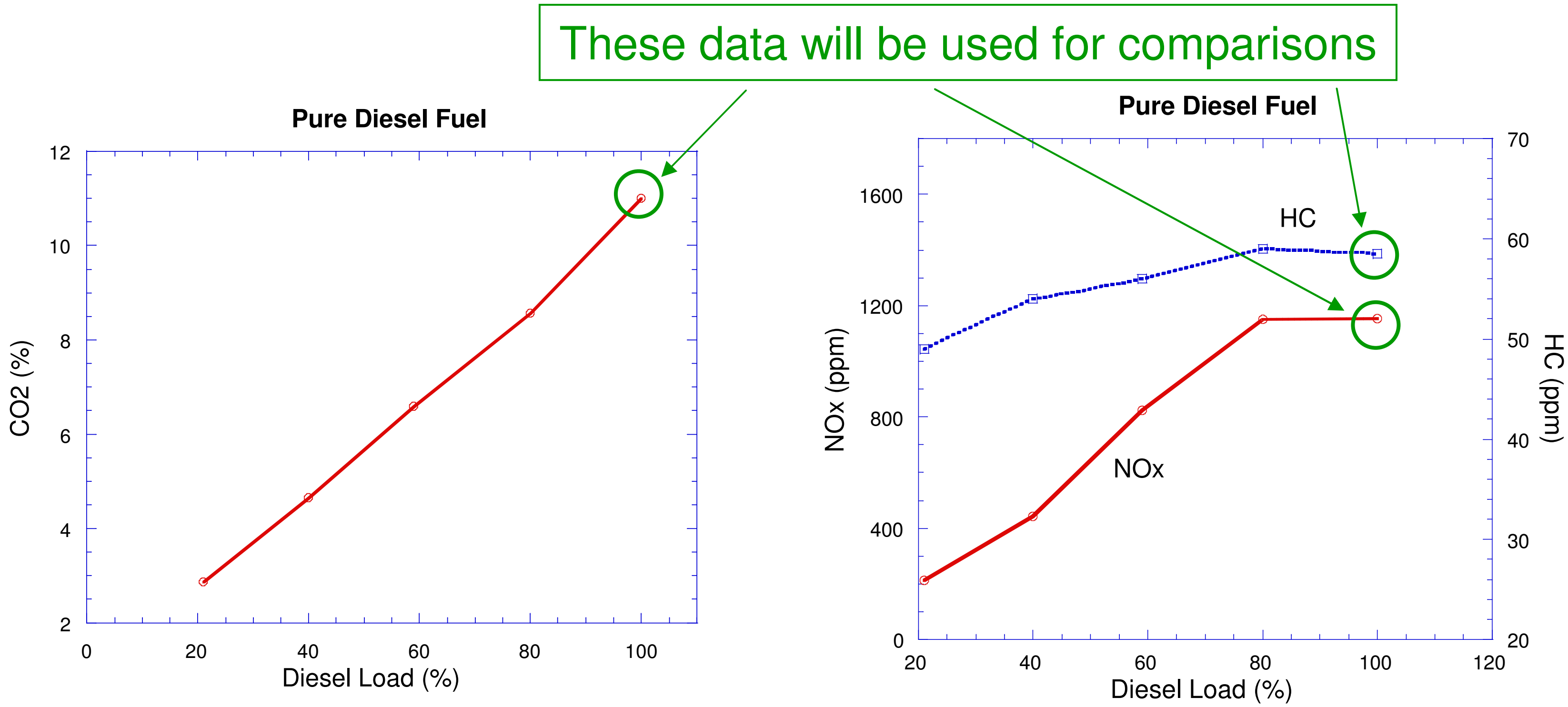


Variable engine torque



Emissions Measurement

- Gaseous emissions – HC, CO, CO_2, NO_x, O_2
- Emission analyzer modification for this study
  - Certain materials were replaced by stainless steel
- Baseline diesel conditions



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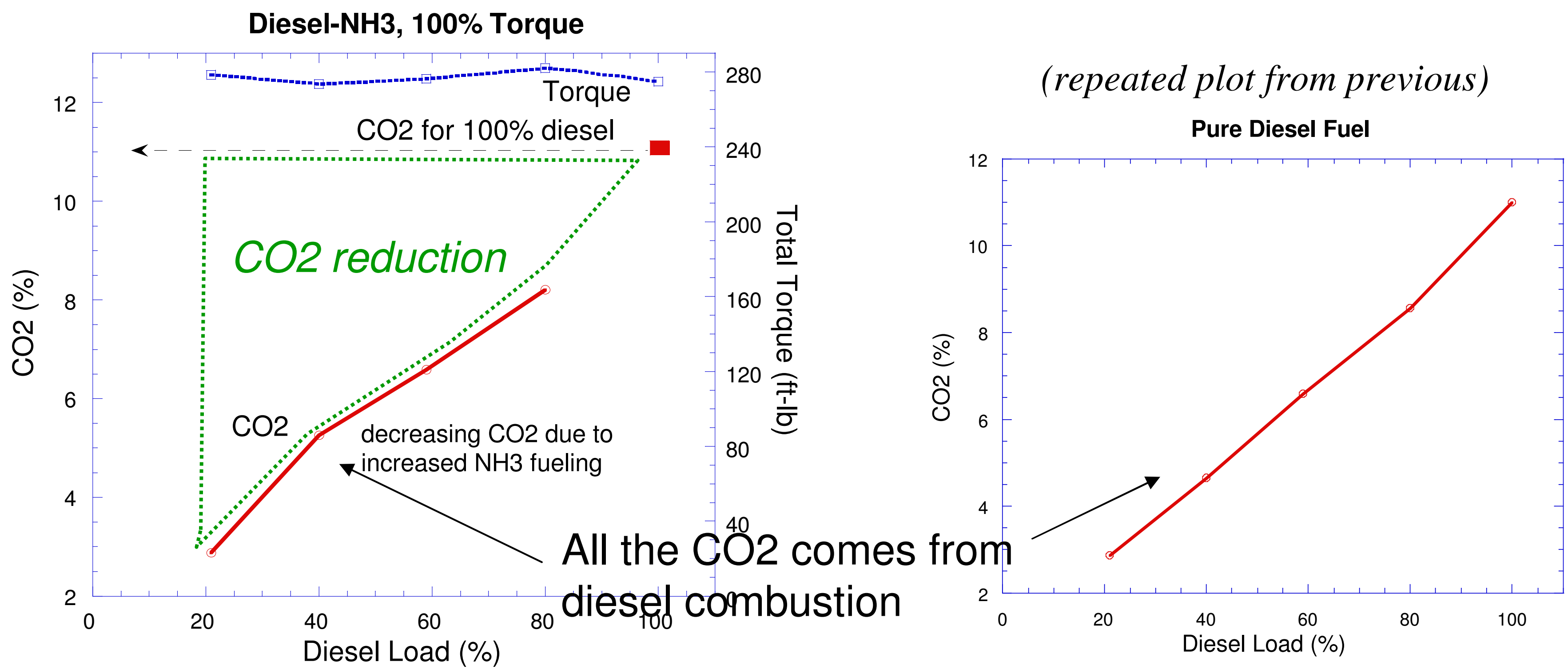
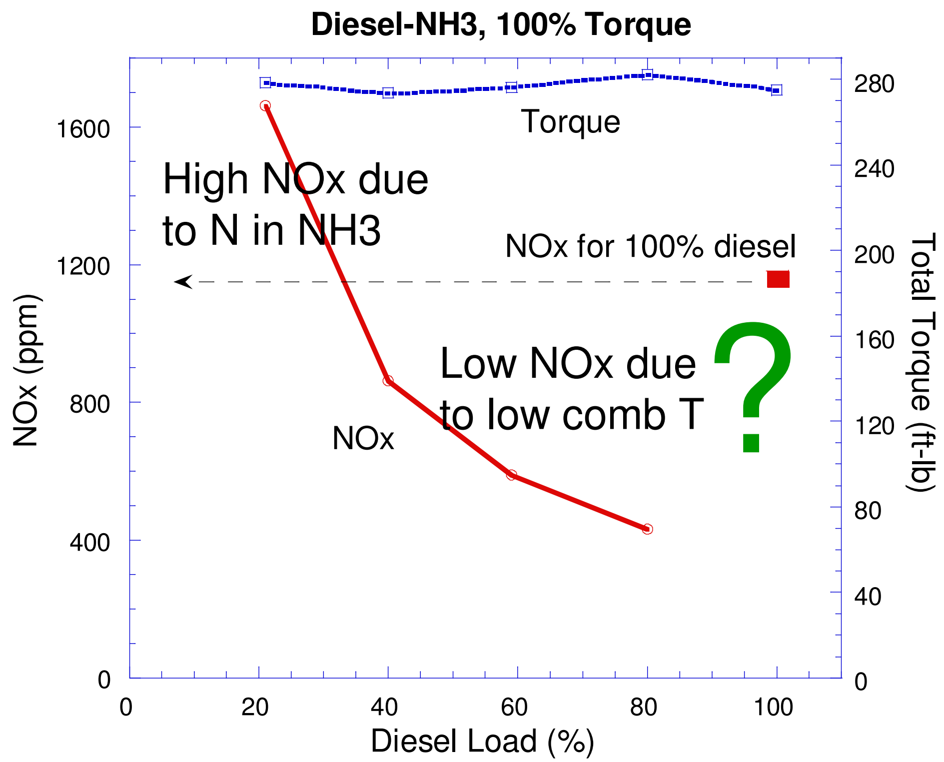
CO2 Results

- Maintained constant torque by varying diesel & NH3



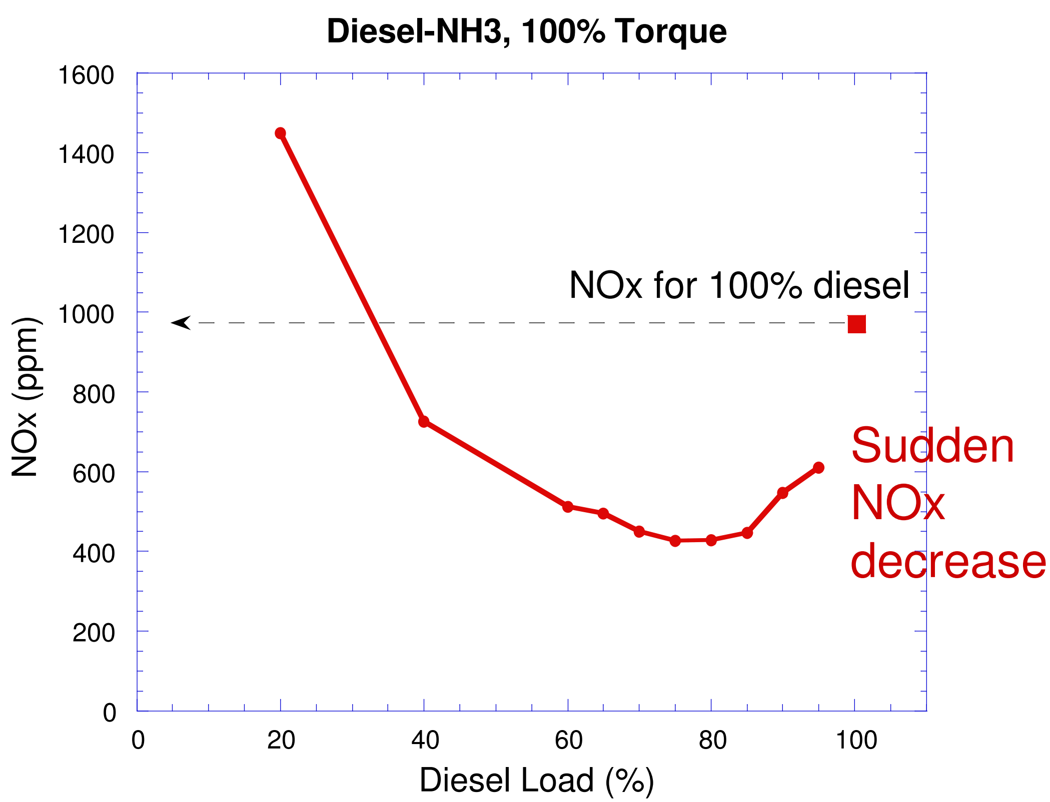
NH3 Results

- Speculation – burning NH3 will …..
  - Increase NOx – due to fuel-bound nitrogen
  - Reduce NOx – due to lower combustion temperature
- Constant torque conditions



More on NOx Emissions

- Repeated testing



Another effect – NH3 can reduce NOx in diesel SCR (selective catalytic reduction)

Urea → NH3

(NH2)2CO + H2O → 2NH3 + CO2

SCR Catalyst

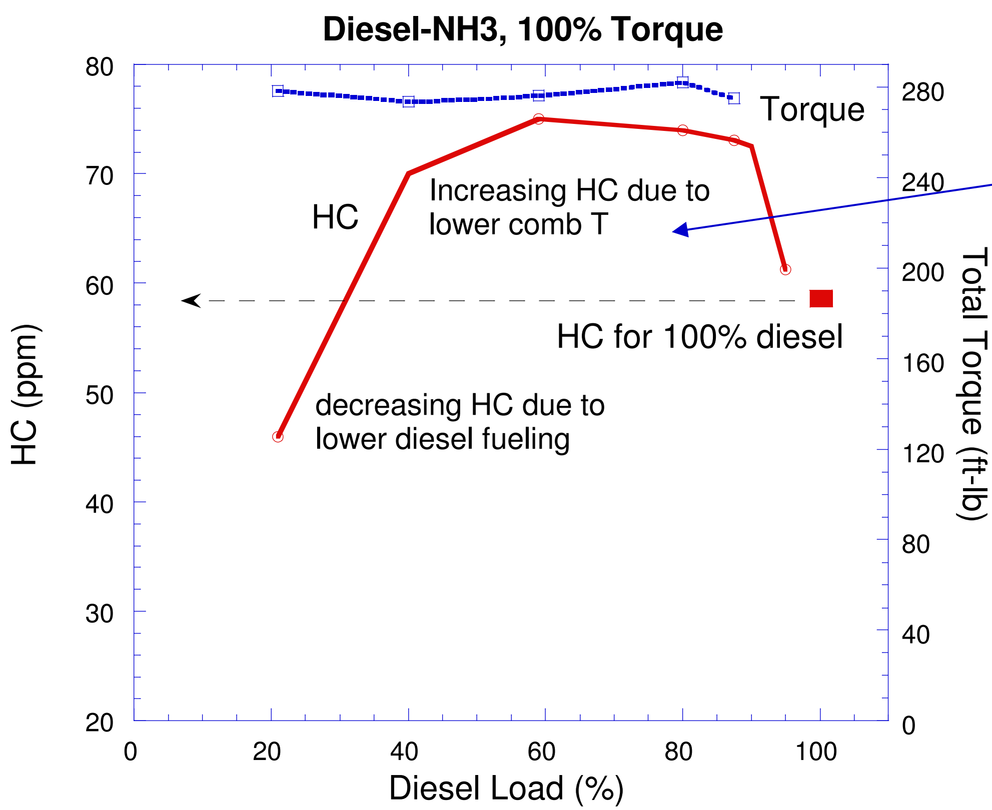
$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$

$$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O$$

HC Results

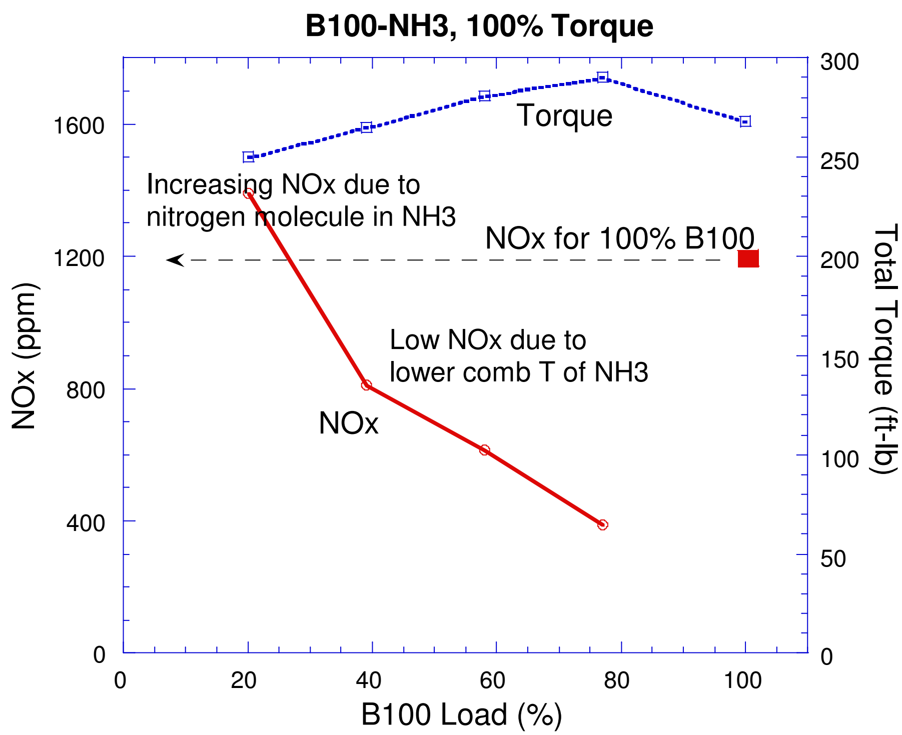
- Maintained constant torque conditions

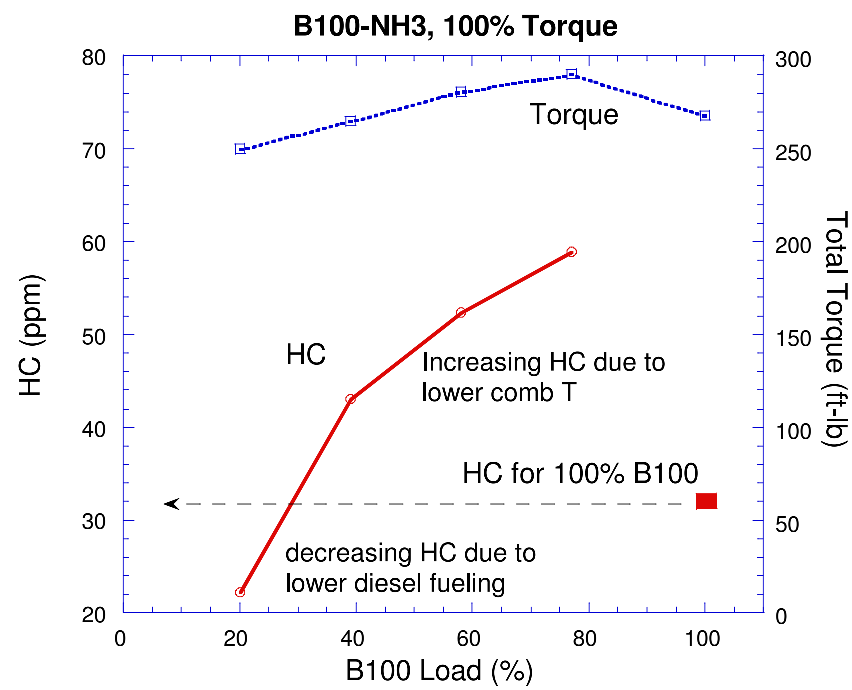


Additional reasons for HC increase?
Re-combination between C (from diesel) and H (from NH3)?

Biodiesel/NH3 Emissions

- Same trend as in the diesel case
  - B100 produced lower HC than regular diesel at baseline





Summary

- Demonstrated ammonia combustion in diesel engines
  - Premixed NH3/air with direct-injection diesel for ignition
  - Effective in CO2 reduction while maintaining the same engine torque output
- Reasonable fuel economy between 20~60% diesel fueling
- NOx emissions are not a concern as originally expected
  - Lower NOx for certain diesel fueling range
  - HC has an opposite trend to NOx
- Further investigations are required for –
  - Emissions formation mechanisms
  - Precise control of NH3/diesel flow rates for optimal fuel economy and exhaust emissions