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

Matthias Veltman
Dr. Song-Charng Kong

Department of Mechanical Engineering
Iowa State University

Acknowledgements:
Iowa Energy Center (Norman Olson, Kevin Nordmeyer)
Robert Bosch LLC (Thomas Stach)

Agenda

- Background
- History of ammonia as a carbon-free fuel at Iowa State University
- Current project
  - Introduction
  - Engine and experimental setup
  - Injection system
  - Next steps
- Future projects
  - NO_x & NH_3 exhaust gas aftertreatment

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
  - 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. [°C]	Storage Pressure [kPa]	Density [kg/m³]	Lower Heating Value [MJ/kg]	Stoichiometric Air/Fuel Ratio by Weight	Energy Content [MJ/kg-stoichiometric mixture]	Autoignition Temp. [°C]	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.

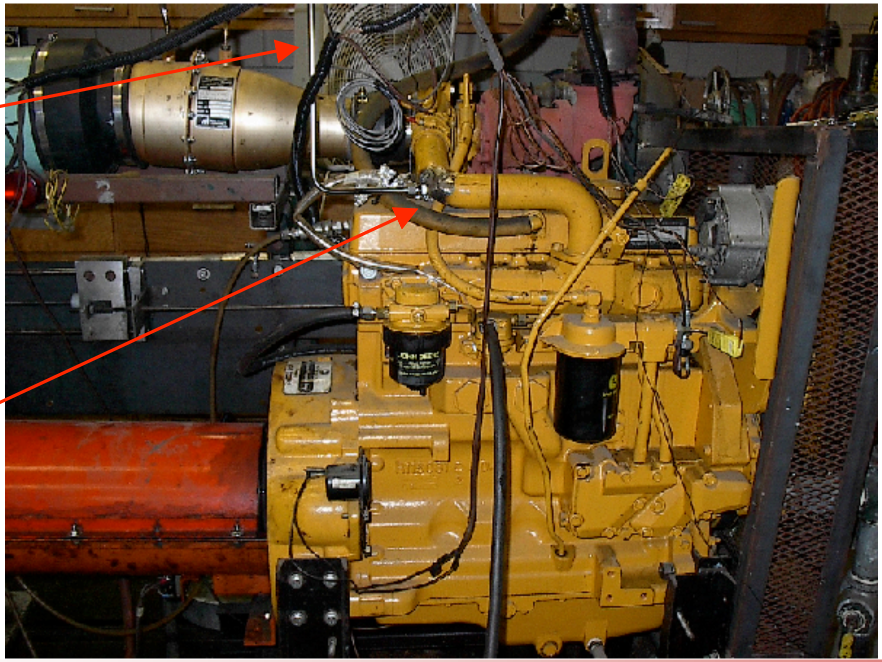
Agenda

- ☑ Background
- ❑ History of ammonia as a carbon-free fuel at Iowa State University
- ❑ Current project
  - Introduction
  - Engine and experimental setup
  - Injection system
  - Next steps
- ❑ Future Projects
  - NO_x & NH_3 exhaust gas aftertreatment

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

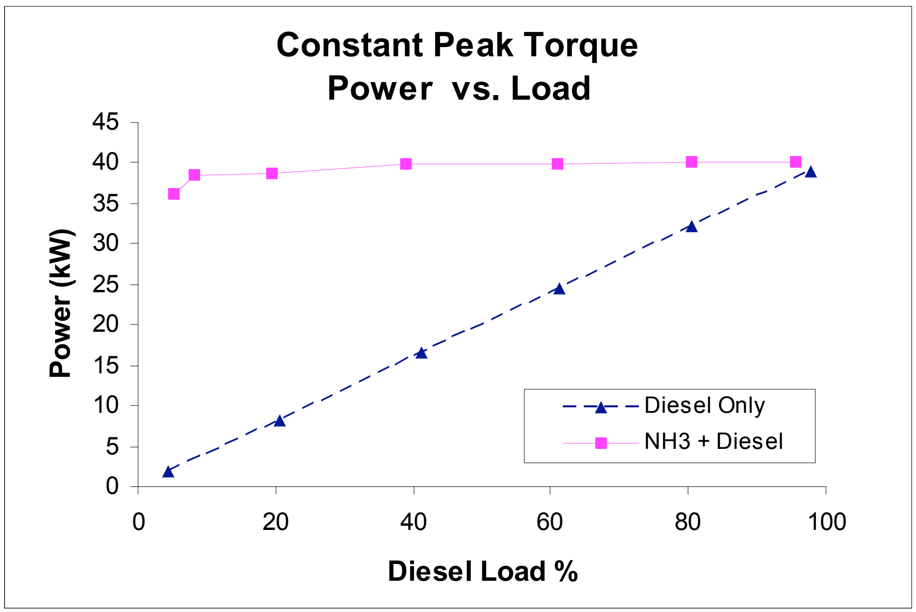
Ammonia fuel line

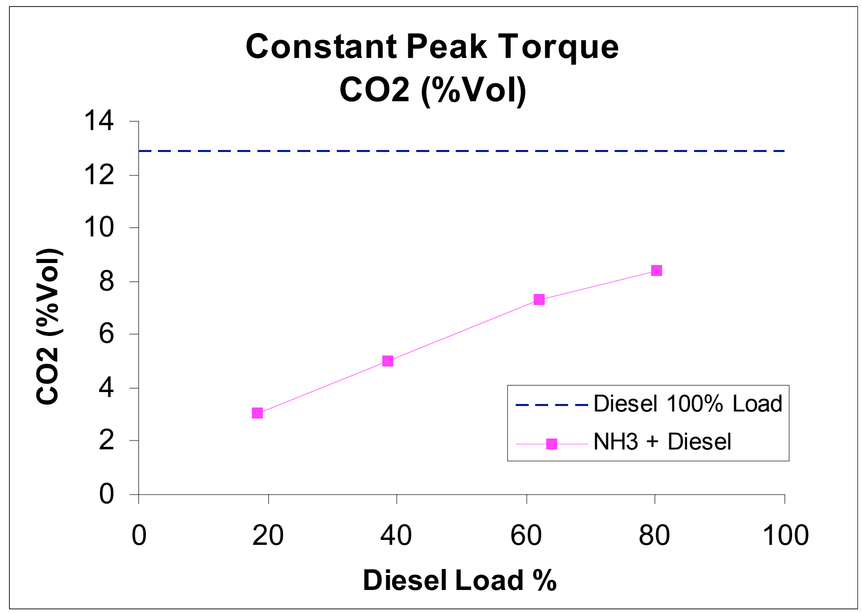


Induction point

Engine Test Results

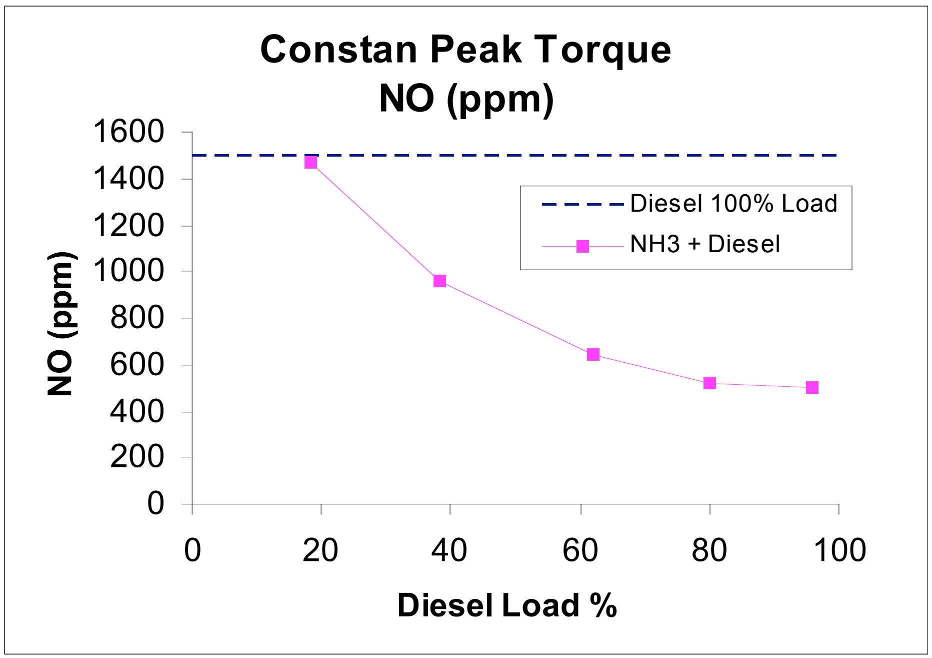
- Obtained stable engine power output
- Low CO_2 emissions
- Reasonable fuel economy between 40~60% diesel fueling
- Ammonia combustion efficiency ~ 95%

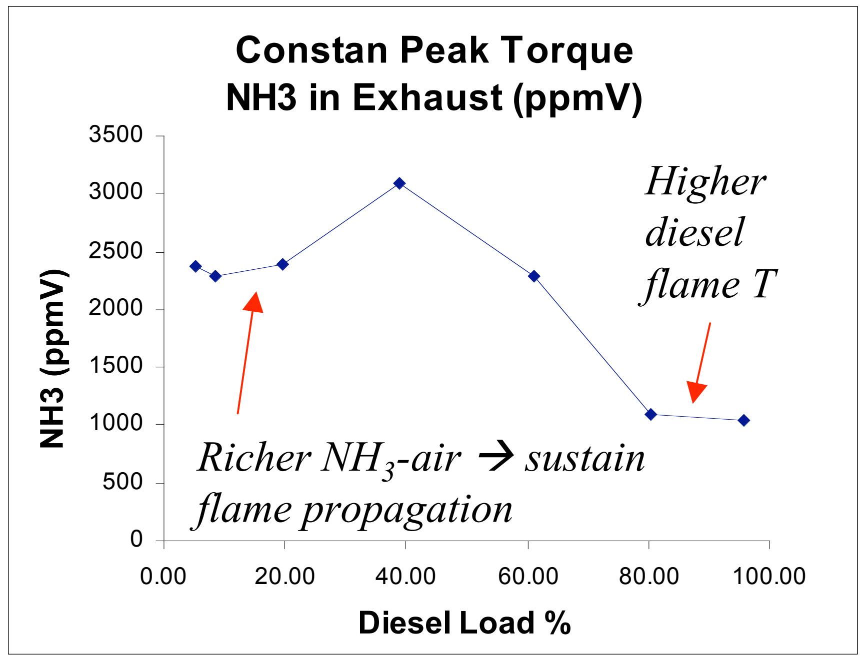




NO & NH_3 Emissions

- 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.





Agenda

- ☑ Background
- ☑ History of ammonia as a carbon-free fuel at Iowa State University
- ❑ Current pProject
  - Introduction
  - Engine and experimental setup
  - Injection system
  - Next steps
- ❑ Future projects
  - NO_x & NH_3 exhaust gas aftertreatment

Introduction

- To improve combustion of ammonia in diesel engines the following obstacles/problems need to be addressed:

Challenges:

1. Reduction of NH_3 emissions.
2. Simplification of injection system.

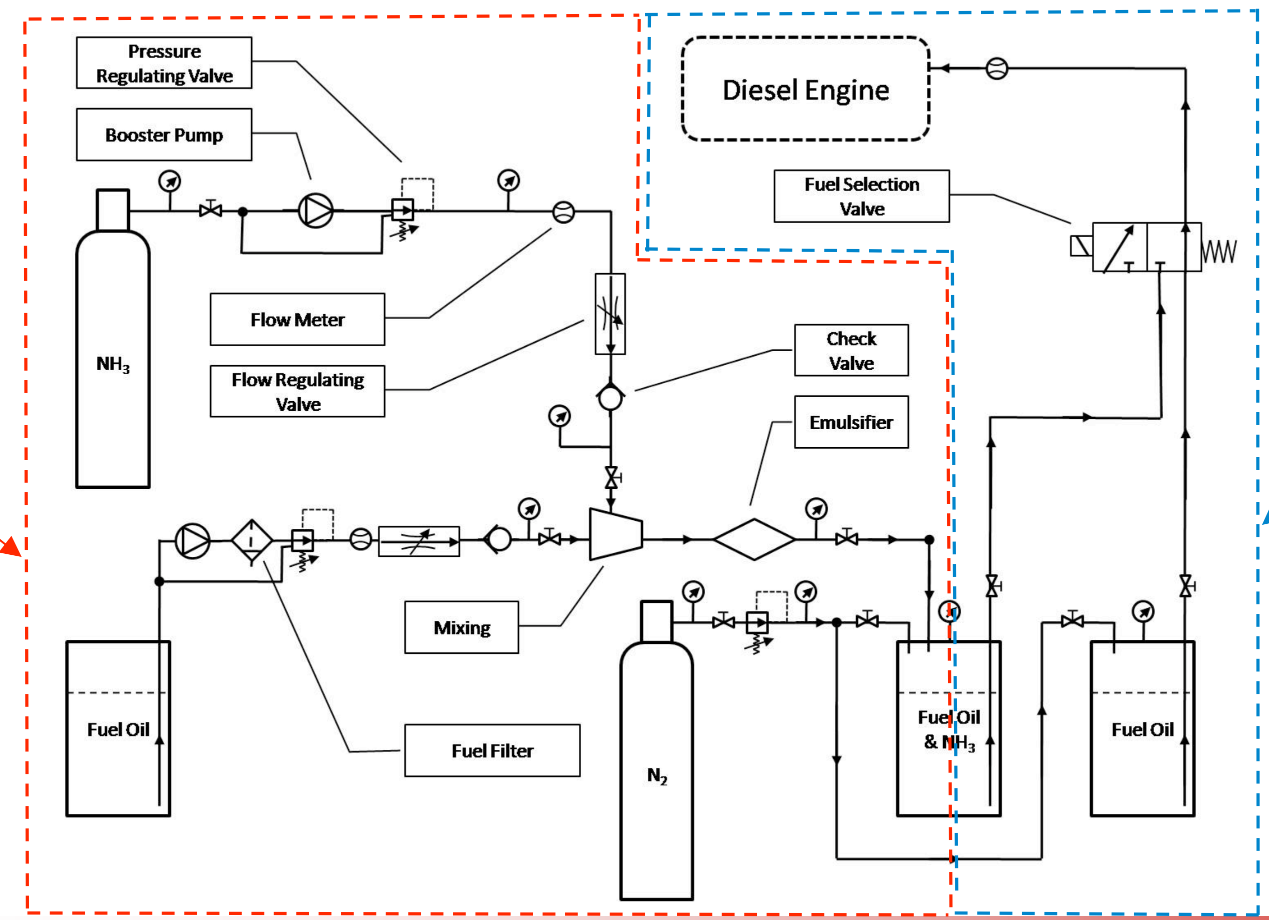
Solution:

1. Apply advanced direct injection strategies
2. Eliminate need for dual fuel system by mixing NH_3 and secondary fuel

Experimental Setup: Fuel Preparation

- Ammonia and a secondary fuel, which will provide ignition energy during combustion, are mixed in a separate facility (no longer part of vehicle)

Separate fuel preparation system/facility



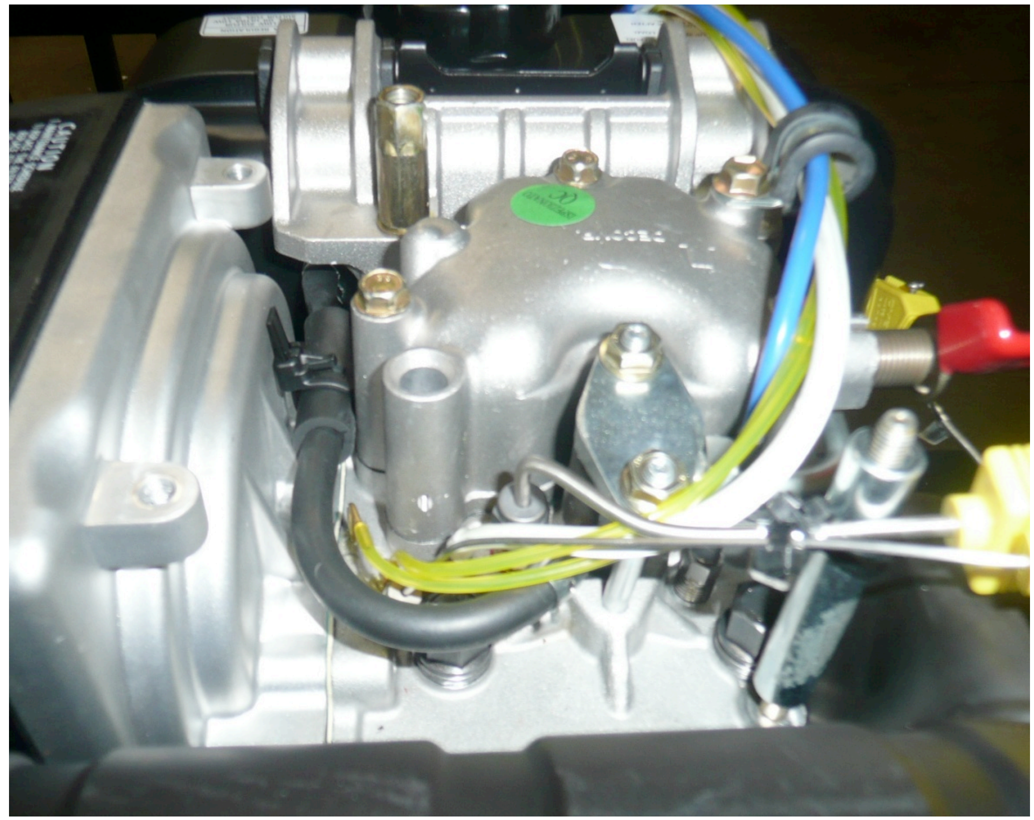
Engine test stand / vehicle

Experimental Setup: Engine

- Yanmar single cylinder direct injection diesel engine
- Highly modified 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	Mechanical Injection System
Injection Pump	Stanadyne Single-Barrel Pump
Injector Nozzle	Sacless (VCO) / 150º Included Spray Angle

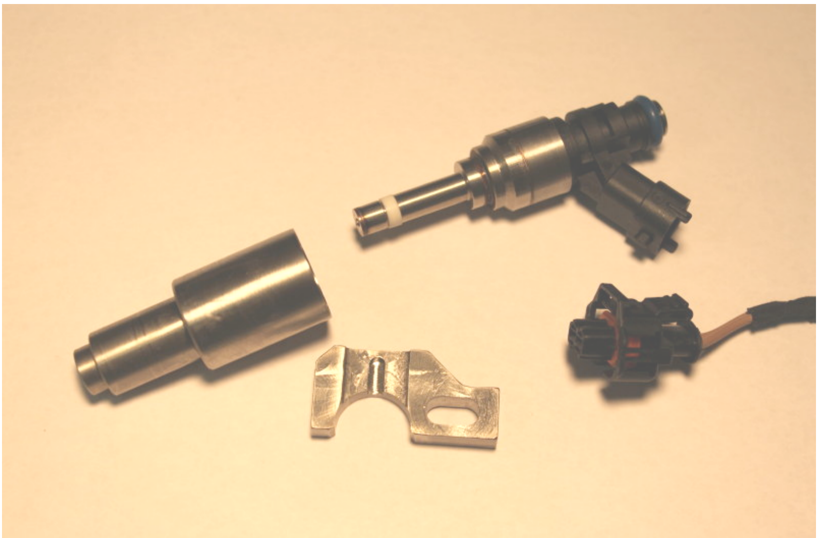
Experimental Setup: Engine

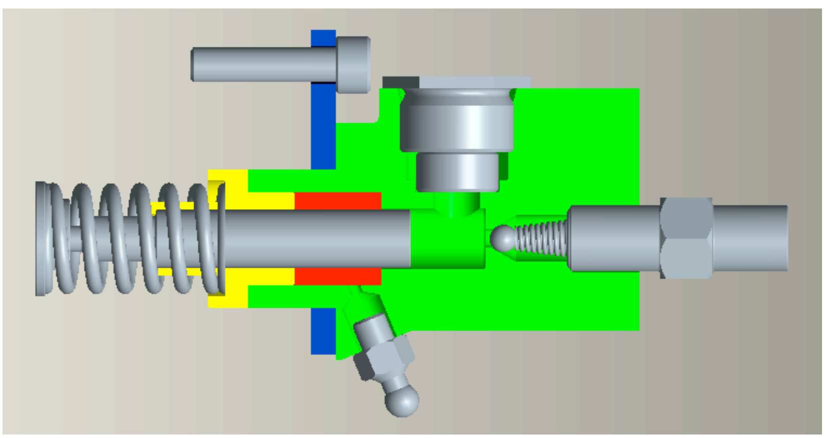


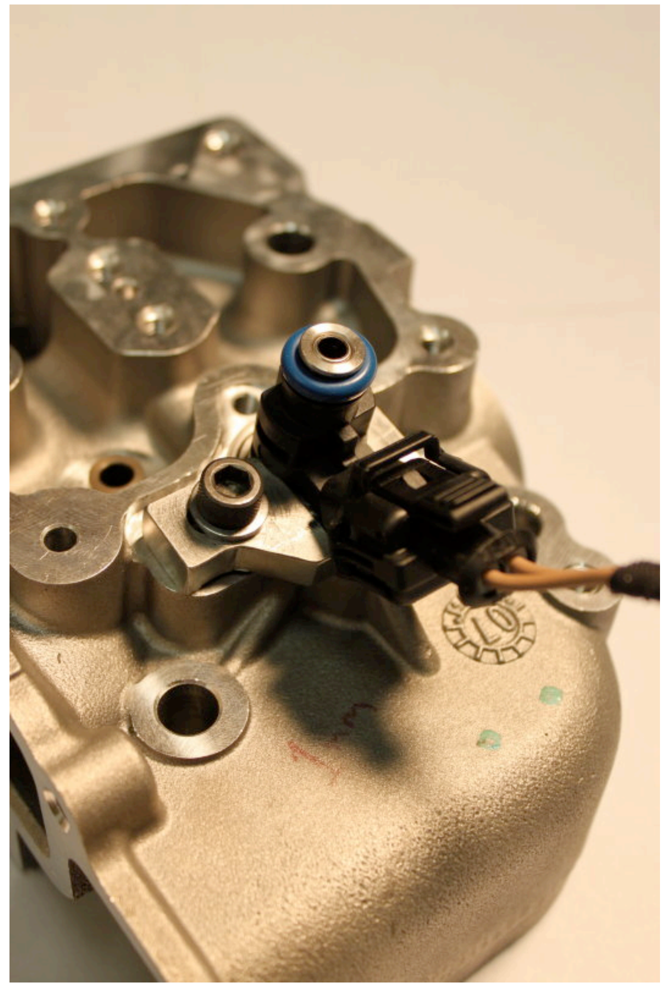
Experimental Setup: Injection System

- Electronically controlled common rail direct fuel injection with up to five injection events per engine 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:
  - Modified Stanadyne high pressure fuel pump (stock pump)
  - Custom design by Iowa State University
- Engine Control Unit
  - Hardware: National Instruments CompactRIO system
  - Injector driver: Iowa State University
  - Software: Iowa State University

Experimental Setup: Injection System







Experimental Setup: Next Steps

- Benchmarking of Yanmar engine in its stock configuration
- Replace fuel injection system
- Develop injection strategies for combustion of ammonia
  - Targets:
    - Near zero ammonia concentration in exhaust (10 ppm or less)
    - Thermal efficiency comparable to conventional diesel engine ($\geq$ 40%)
    - Low NO_x emissions ($\leq$7.5 g/kWh – Tier 4)
    - High ammonia content in fuel mixture ($\geq$ 90%)
    - Useful engine map comparable to that of base engine

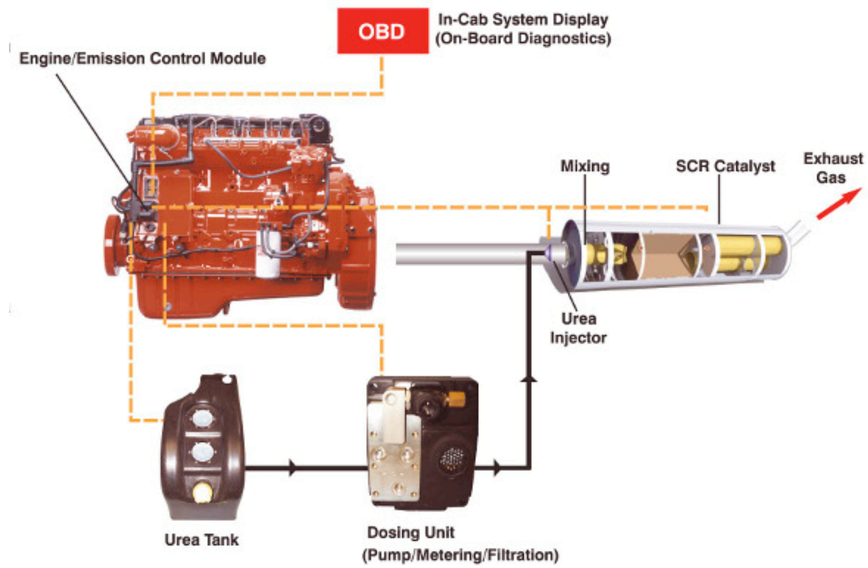
- Vision: Have engine ready to power a small utility vehicle in the near future.

Agenda

- ☑ Background
- ☑ History of ammonia as a carbon-free fuel at Iowa State University
- ☑ Current project
  - Introduction
  - Engine and experimental setup
  - Injection system
  - Next steps
- ❑ Future Projects
  - NO_x & NH_3 exhaust gas aftertreatment

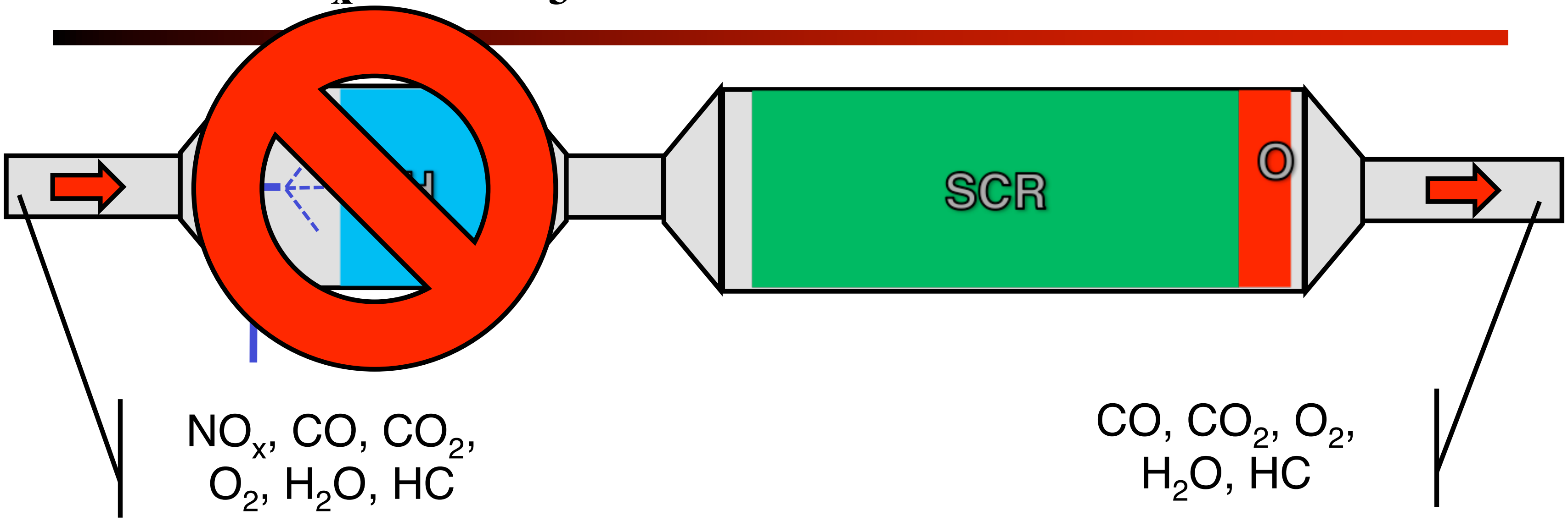
NO_x & NH_3 Exhaust Gas Aftertreatment

- NO_x aftertreatment by means of Selective Catalytic Reduction (SCR)
- Widely used with commercial and passenger vehicles in Europe
- Working principle:
  - Aqueous urea solution is injected into the hot exhaust and converted to ammonia utilizing a hydrolysis catalyst
  - Ammonia then reacts with NO_x and oxygen to nitrogen and water
  - An ammonia oxidation catalyst oxidizes excess ammonia



Picture: Cummins Inc.
(www.everytime.cummins.com)

NO_x & NH_3 Exhaust Gas Aftertreatment

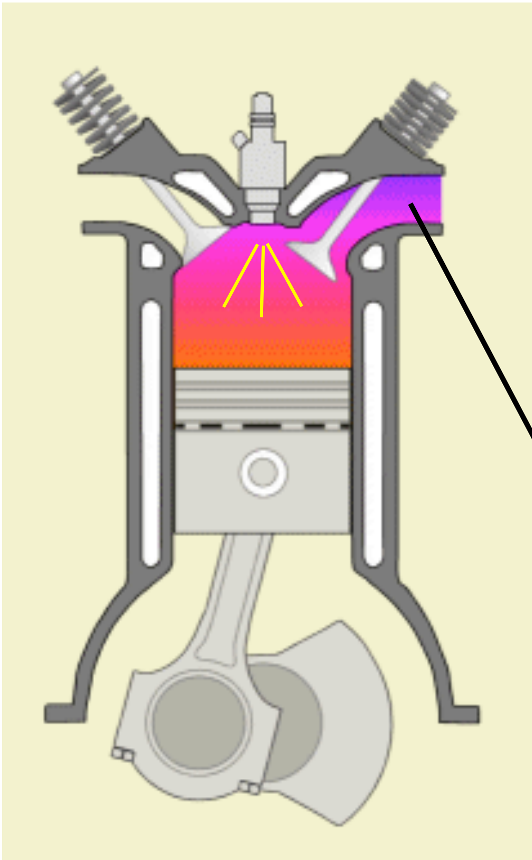


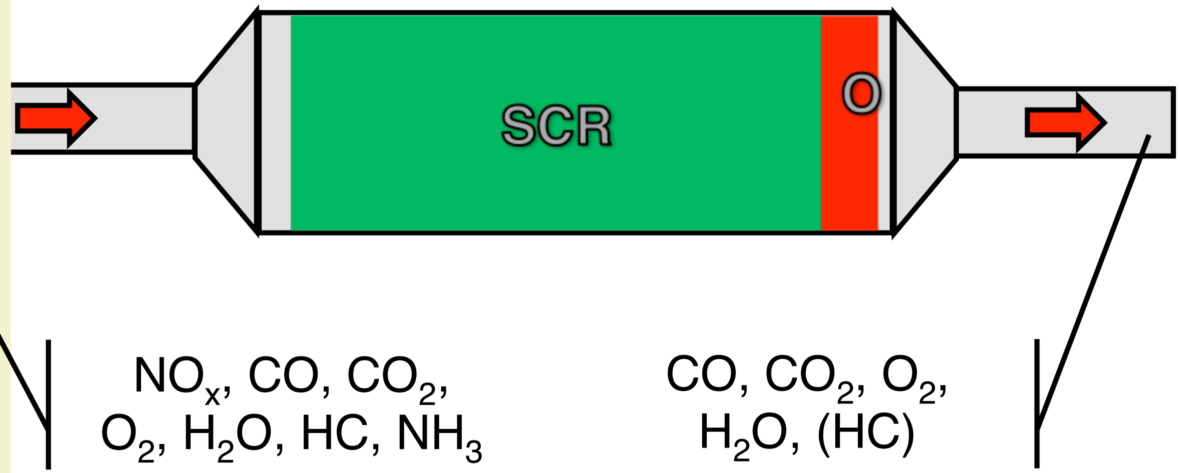
$(NH_2)_2CO \Rightarrow NH_3 + HNCO$
$HNCO + H_2O \Rightarrow NH_3 + CO_2$

$6NO + 4NH_3 \Rightarrow 5N_2 + 6H_2O$
$4NO + 4NH_3 + O_2 \Rightarrow 4N_2 + 6H_2O$
$6NO_2 + 8NH_3 \Rightarrow 7N_2 + 12H_2O$
$2NO_2 + 4NH_3 + O_2 \Rightarrow 3N_2 + 6H_2O$
$NO + NO_2 + 2NH_3 \Rightarrow 2N_2 + 3H_2O$

$4NH_3 + 3O_2 \Rightarrow 2N_2 + 6H_2O$

NO_x & NH_3 Exhaust Gas Aftertreatment





$$6NO + 4NH_3 \Rightarrow 5N_2 + 6H_2O$$
$$4NO + 4NH_3 + O_2 \Rightarrow 4N_2 + 6H_2O$$
$$6NO_2 + 8NH_3 \Rightarrow 7N_2 + 12H_2O$$
$$2NO_2 + 4NH_3 + O_2 \Rightarrow 3N_2 + 6H_2O$$
$$NO + NO_2 + 2NH_3 \Rightarrow 2N_2 + 3H_2O$$

$$4NH_3 + 3O_2 \Rightarrow 2N_2 + 6H_2O$$

Agenda

- ✓ Background
- ✓ History of ammonia as a carbon-free fuel at Iowa State University
- ✓ Current project
  - Introduction
  - Engine and experimental setup
  - Injection system
  - Next steps
- ✓ Future Projects
  - NO_x & NH_3 exhaust gas aftertreatment