Advancement of Gasoline Direct Injection Compression Ignition (GDCI) for US 2025 CAFE and Tier3 Emissions

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Innovation for the Real World

Motivation and Industry Challenge

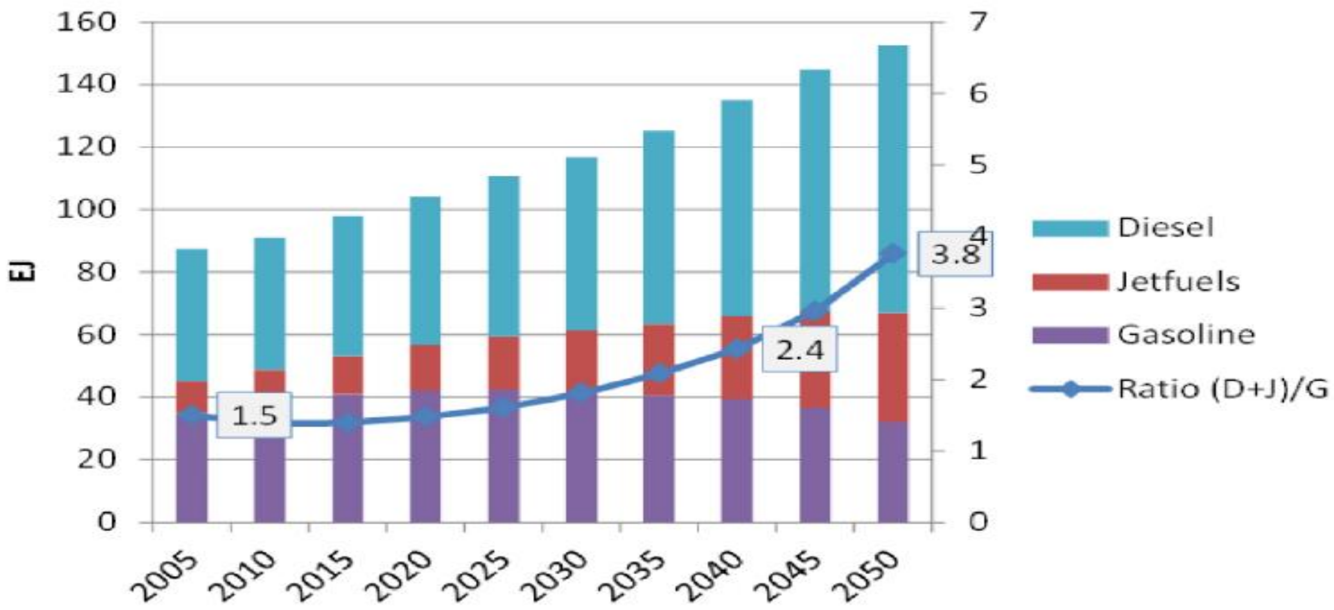
- Stringent CAFE and CO2 targets with US Tier 3 emissions laws
- Changing demand for diesel and gasoline fuels worldwide
- Need efficient and clean engines operating on gasoline-like fuels

Fuel Economy (United States)

Year	CAFE Target (MPG)	CO_2 Target (gCO_2/mile)
2011	27.6	322
2016	35.3	250
2025	54.5	163

4. World Energy Council. 2011. Global Transport Scenarios 2050. WEC London

Projected Fuel Demand (World Energy Council, 2011)



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Top Goals for Future Internal Comb. Engines

- Ultra high fuel efficiency
  - Target: 200 g/kWh (42% thermal efficiency)
  - Responsible use of non-renewable fossil fuels
  - High well-to-wheel (WTW) fuel efficiency
- Minimize GHG emissions for life cycle of vehicle
  - Includes CO2 emissions to process the fuel, manufacture vehicle, and combust fuel
- Ultra low criteria emissions both on cycle & off cycle (US Tier3-Bin30)
  - NOx, HC, PM, CO, CH2O

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Three Main GDCI Programs at Delphi

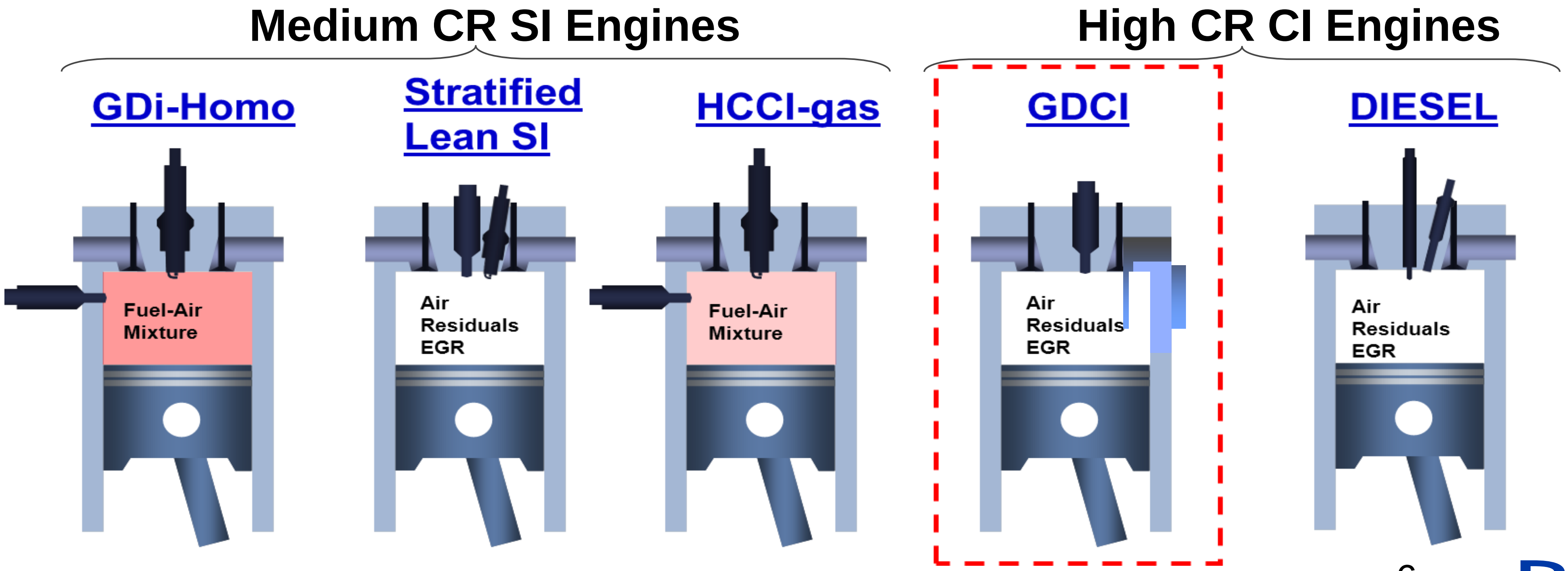
US Dept of Energy	4-Year 2014-2019	Develop GDCI Powertrain and Demonstrate 35% improved FE with Tier3-B30 Emissions in a practical vehicle	ORNL, Umicore, Univ of Wisconsin-Madison
Saudi Aramco	3-Year 2015-2018	Study Fuel Effects and Low Octane Fuels on GDCI Combustion	Saudi Aramco
ARPA-E (DOE)	3-Year 2016-2018	Combine Opposed-Piston engine technology with GDCI for best-in-class fuel efficiency	Achates Power, Argonne National Labs

Delphi is partnered with leading industry experts to develop and commercialize GDCI technology

Contents

GDCI Combines the Best of Diesel & SI Technology

- A new low-temp combustion process for Partially-Premixed CI
- Gasoline that vaporizes & partially mixes at low injection pressure
- High CR with late multiple injections (similar to diesel)
- High effic. & low NOx, PM over wide speed-load range



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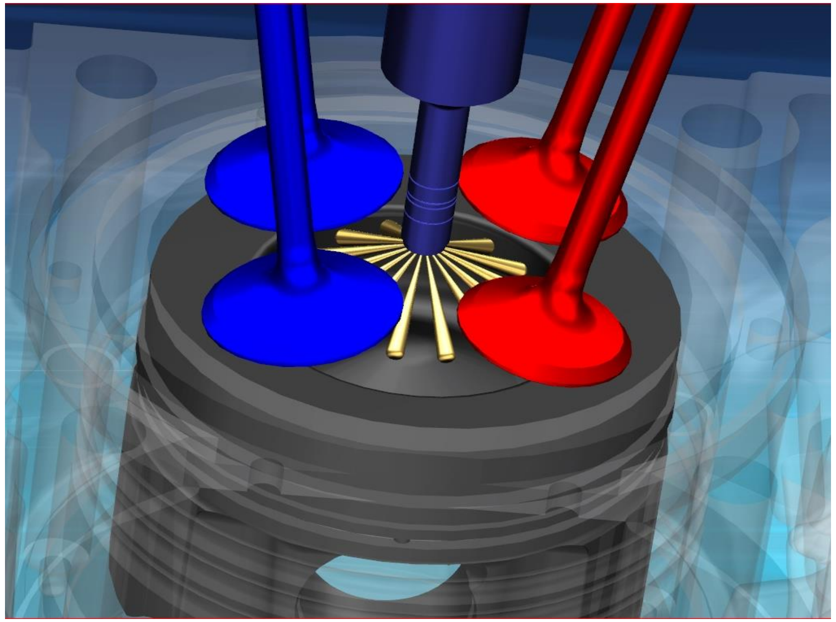
GDCI Engine Concept

- Gasoline Partially Premixed CI
- Fuel Injection
  - Central Mounted, Multiple-Late Injection, GDi-like injection pressures
- Valvetrain – cont.-var. mechanical (exhaust rebreathing)
- Adv EMS – Cyl.-Pres.-Based Control
- No classic SI Knock or Preignition
- Down-sized, down-speeded, & boosted
- High CR, Lean, Unthrottled

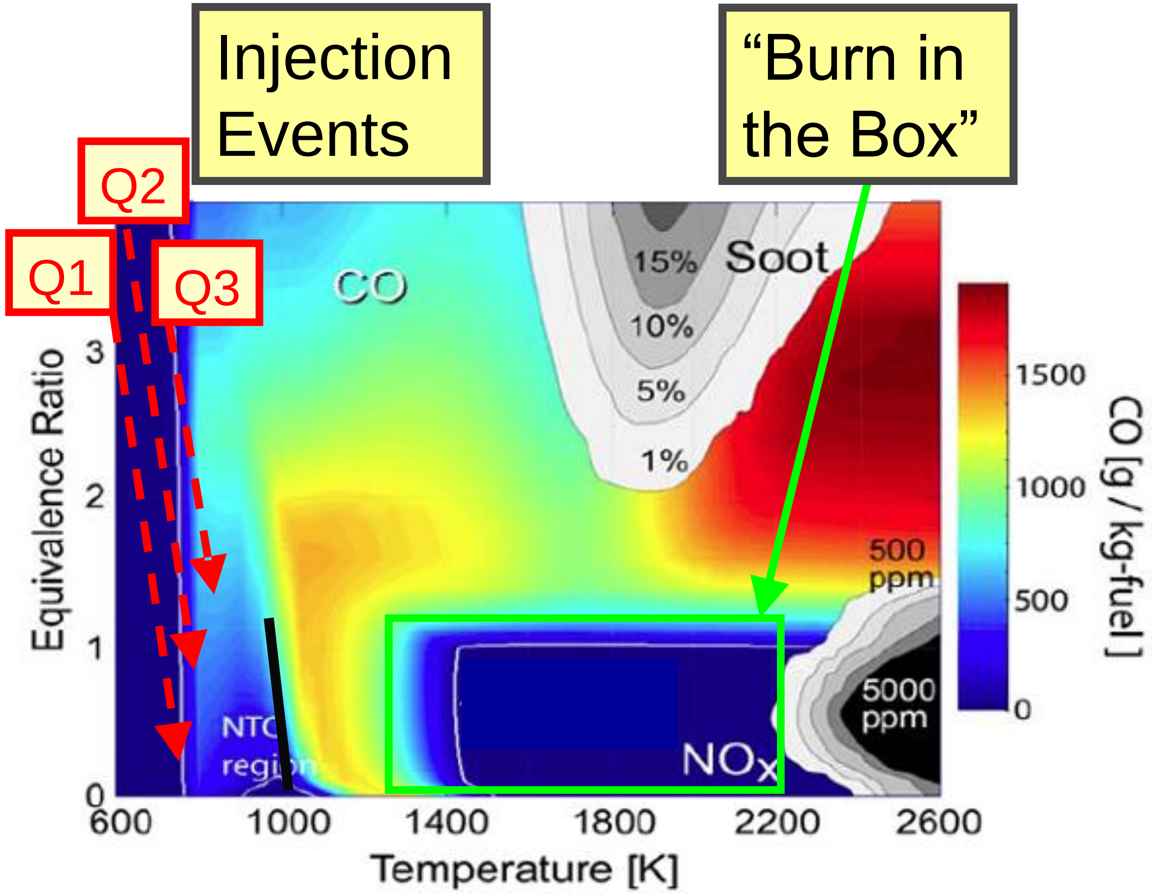
GDCI Concept



Addressing all loss mechanisms for internal combustion engines

GDCI Injection Strategy – Phi-T Diagram

- 1, 2, or 3 injections on Intake and Compression Strokes
- Complete injection & partial mixing prior to start-of-comb.(PPCI)
- “Stratify”: robust ignition and controlled heat release
- “Burn in the Box”: heat release below Phi=1.2, 1200 < T < 2300 K



Simultaneously low NOx, PM, and CO is possible

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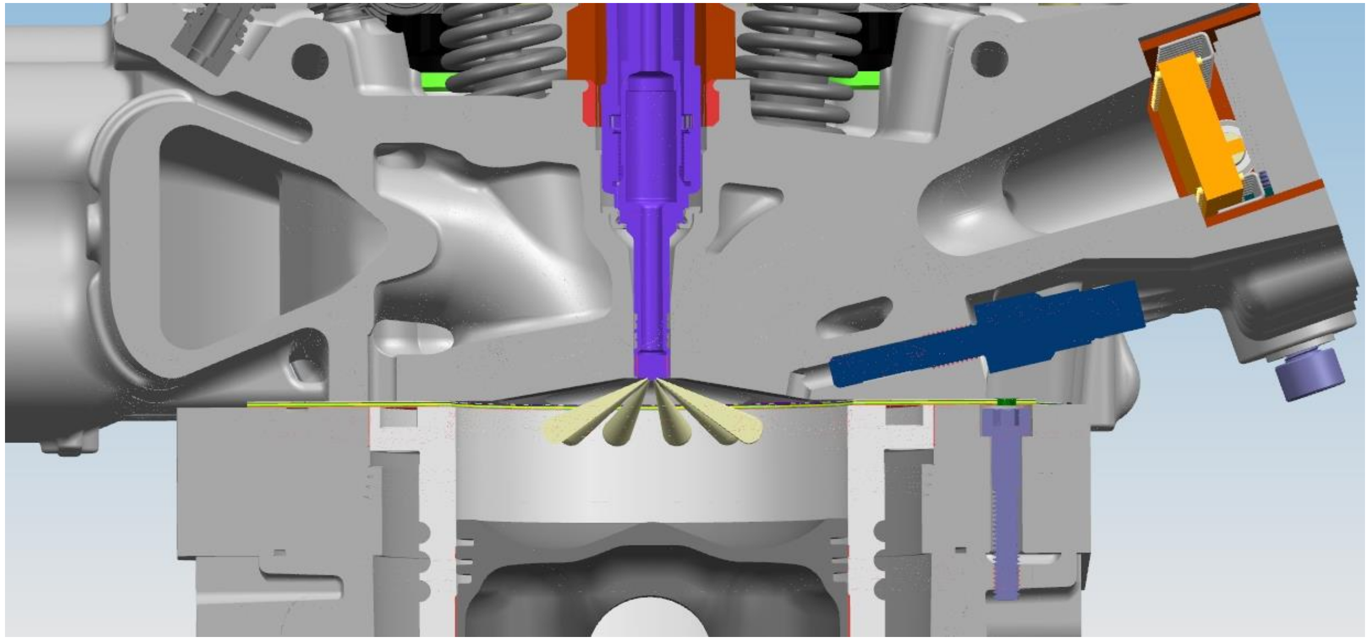
Gen3 GDCI Combustion System

- "Wetless" concept for low smoke
  - Inject at any SOI without wall wetting
  - Wide spray angle matched to bowl
- Long stroke S/B=1.28 increases TDC clr space for late injections (D=2.22 liters)
- Zero swirl & squish for min. heat losses

- GCR: 16:1 (compression)
- Fast Intake Air Heating
- Cylinder Pressure Sensing
- Integral air-gap insulated exhaust manifold
- Pre-turbo catalyst (PTC)



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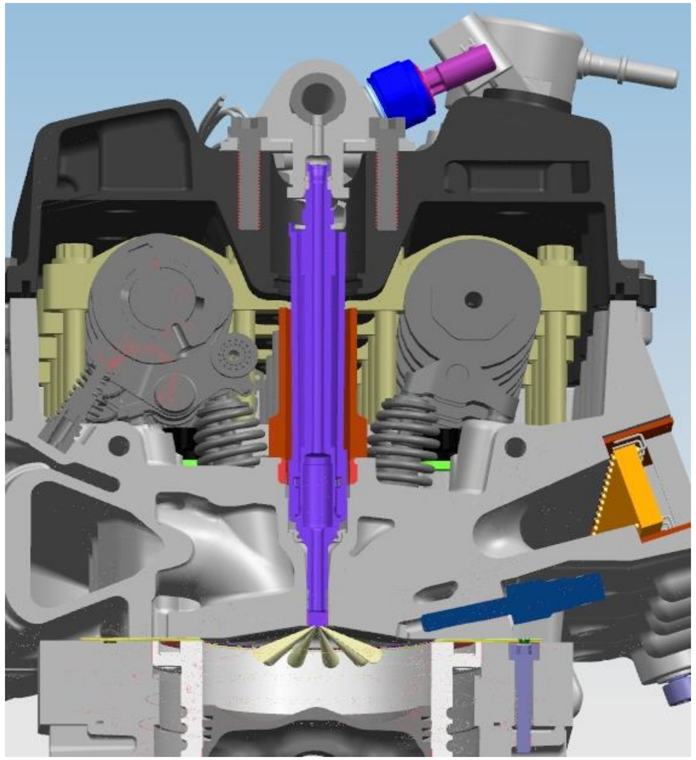
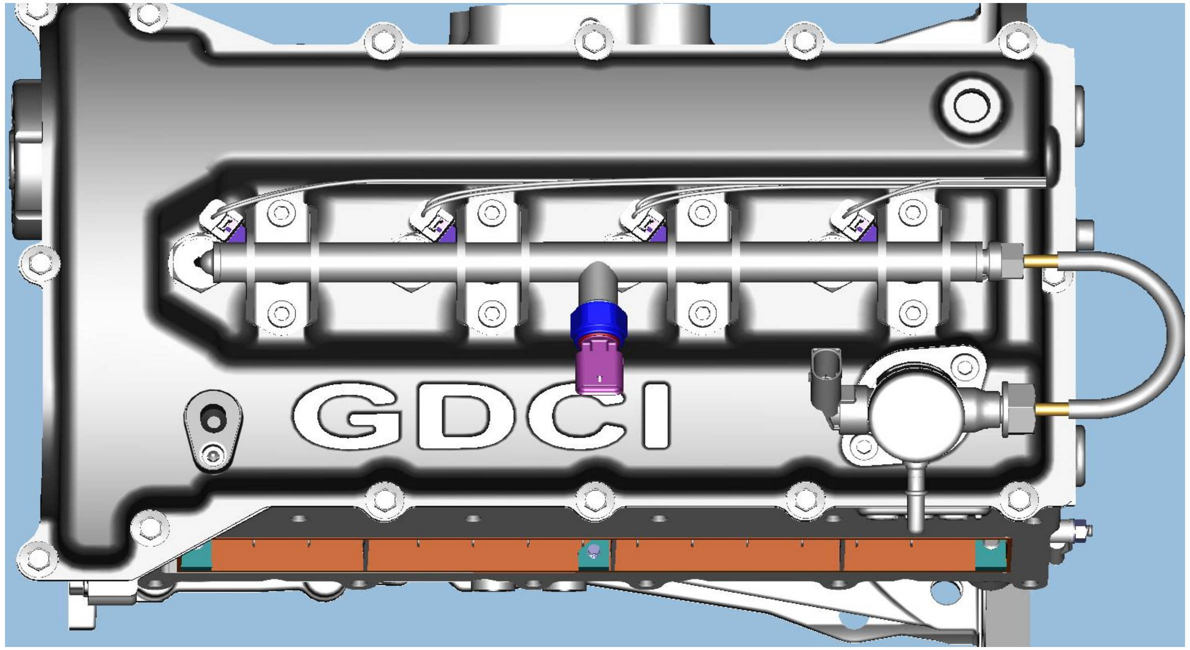
Gen3 GDCI Injection System

- Centrally-mounted, GDi Injectors with high injection rate
  - 350+ bar injection pressure
- Fuel pump driven by Intake Cam
- Sprays developed for fast atomization without wetting





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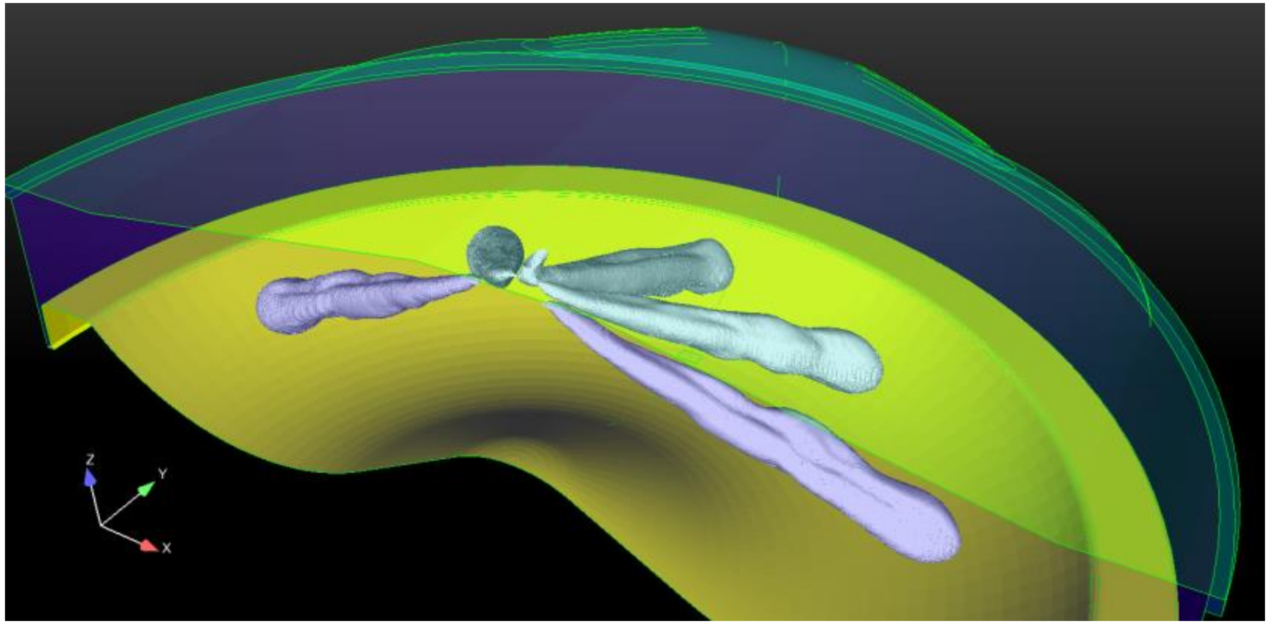
Combustion System Development

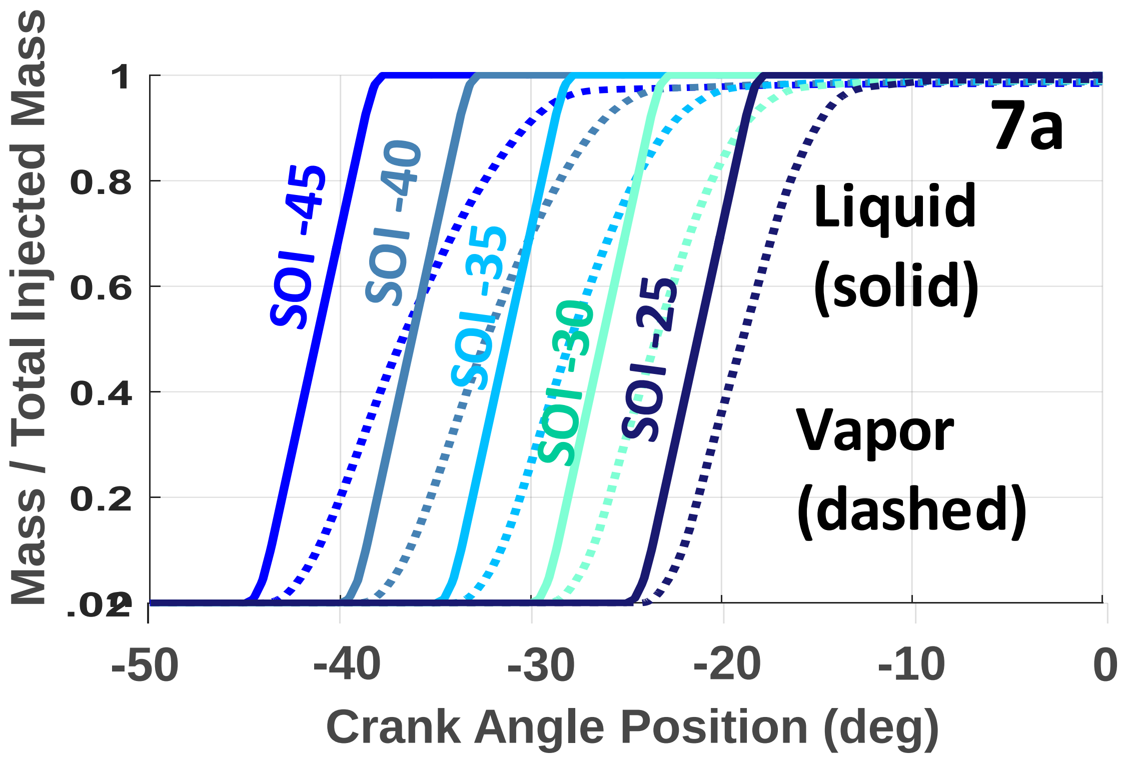
- Goal: "wetless" combustion system for minimal smoke emissions
- Optimize spray and piston bowl design for both early and late injections
- Preinjections on intake stroke create premixed charge (PHI floor)
- Last injection late on compression stroke controls ignition; determines smoke and NOx emissions



CFD tools used extensively for spray development

CFD Simulation of Injection Process

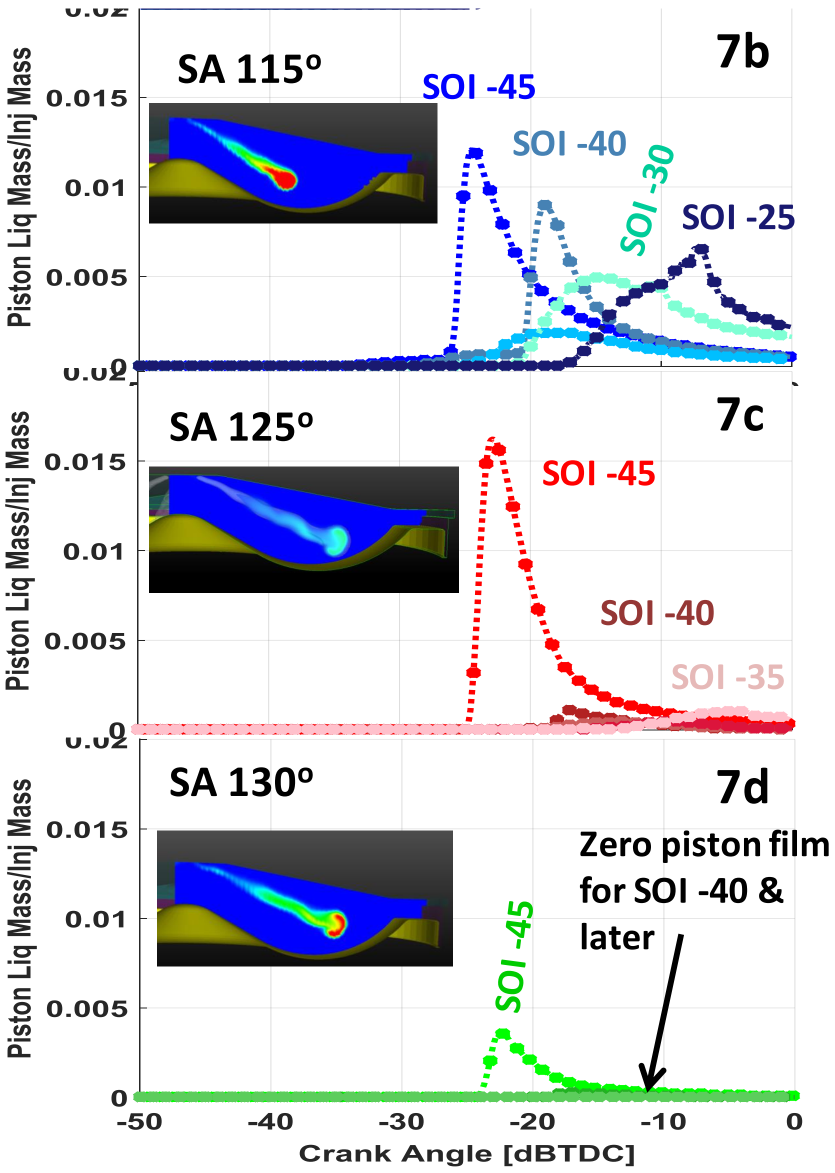
- Plot shows injected fuel and vapor mass as function of time for SOI -45 to -25
- Injection period: 7 CAD (<0.6 ms)
- Very fast vaporization is observed, especially for late injections when cylinder gas temp. and pres. are high
- High cylinder gas temp. and pres. for late injections greatly reduce liquid penetration
    - Major factor to reduce wall wetting



Simulation Results: 3 Spray Angles

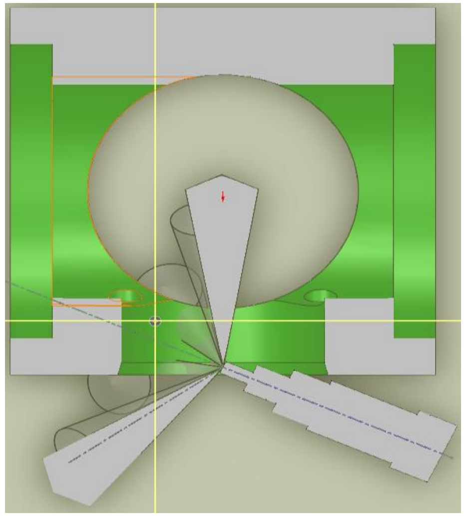
Video

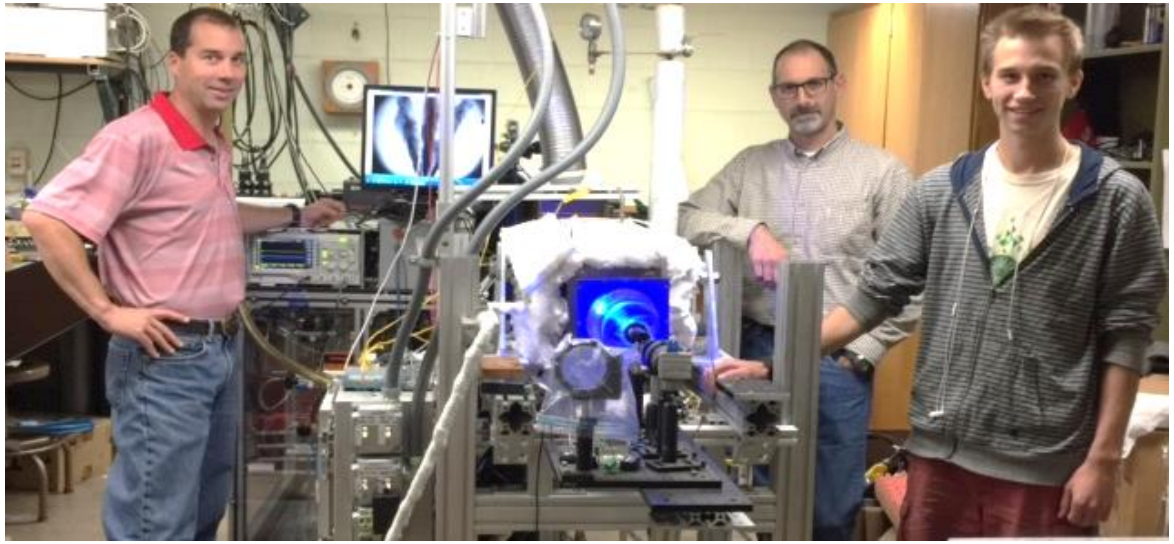
- Spray angle is a key factor in comb. system design
- Plots show piston and liner fuel mass as function of time for three spray angles (115, 125, 130 deg included)
- For spray angle 115, fuel wetting occurs for a range of SOI. Wetting persists at TDC and during combustion.
- For spray angle 125, fuel wetting is reduced
- For spray angle 130 and SOI later than -45, the injection process is “wetless”
- <u>Conclude</u>: wider spray angles of ~130 deg are preferred with Gen3 piston

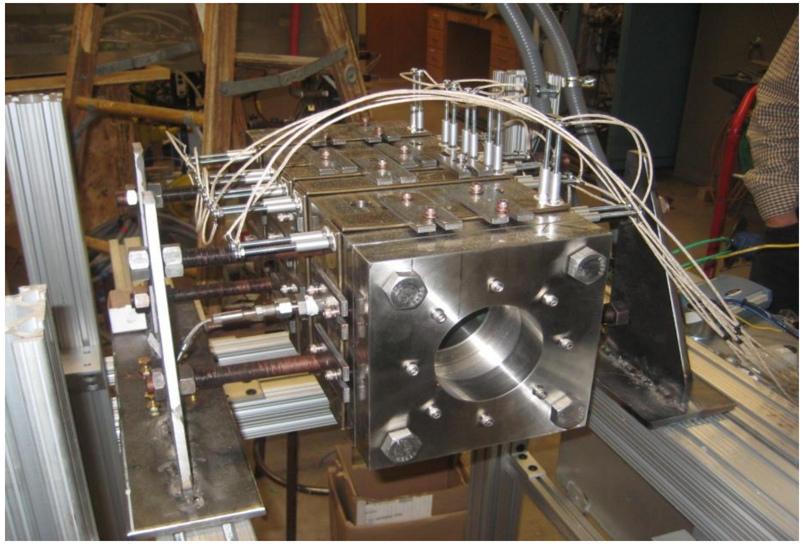


Spray Chamber Testing (UW-Madison)

- High Pressure & Temperature Chamber at UW-Madison (Ghandhi & Oakley)
  - Non-reacting, flow-through type chamber
  - Multi-plume configuration
  - Plume oriented normal to axis of view
- Objectives: Characterize injectors, validate spray models







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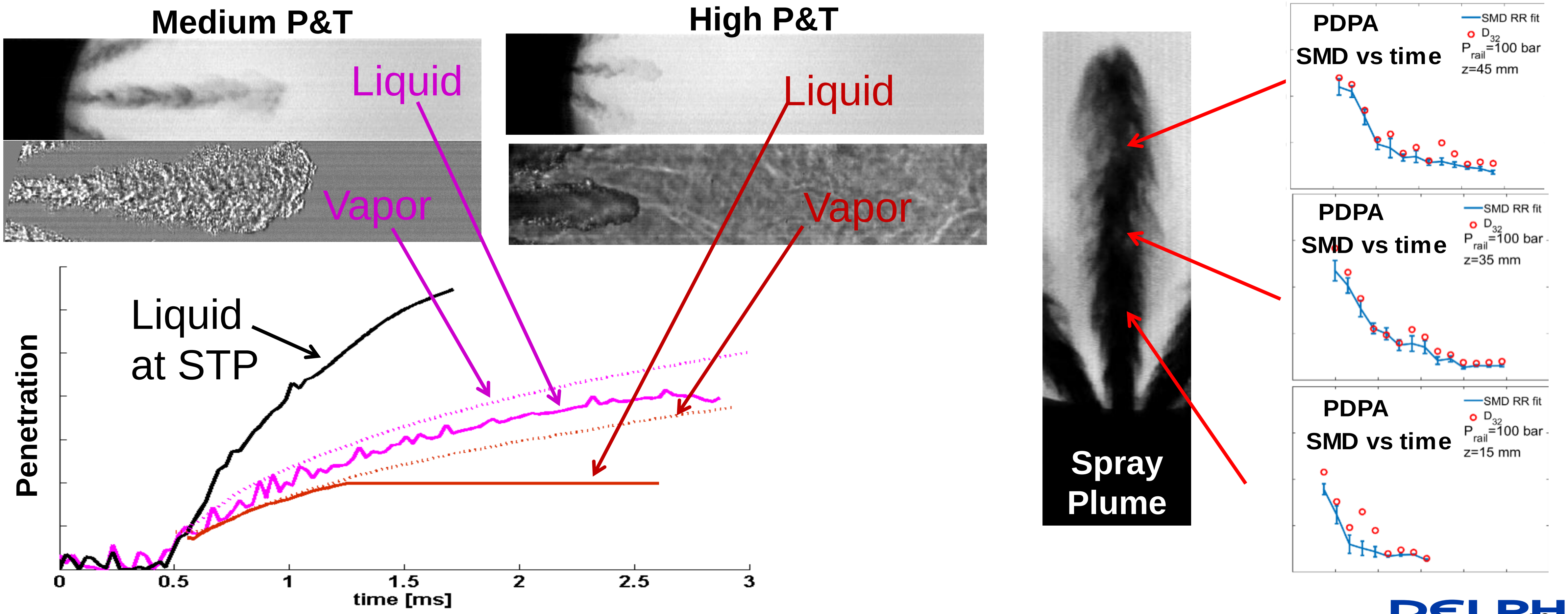
Backlit & Schlieren Images; Drop Size Measurement

- Liquid & Vapor penetration (Q=25mm3, 200bar)
- Low liquid penetration for higher chamber pressures
- Very small drop size (SMD) measured along spray plume (100bar)



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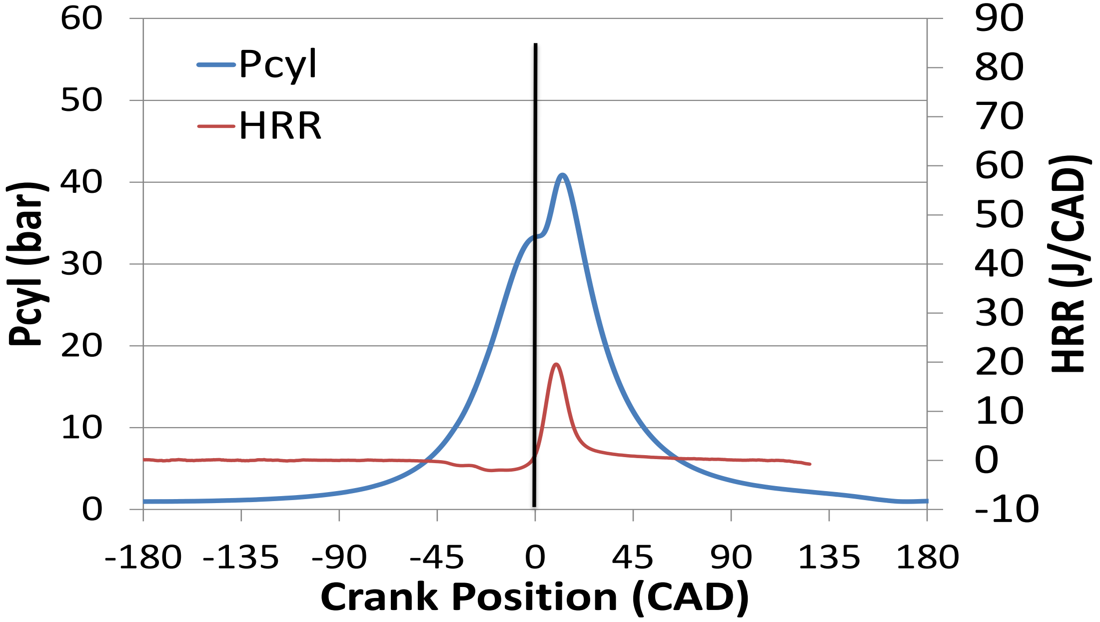
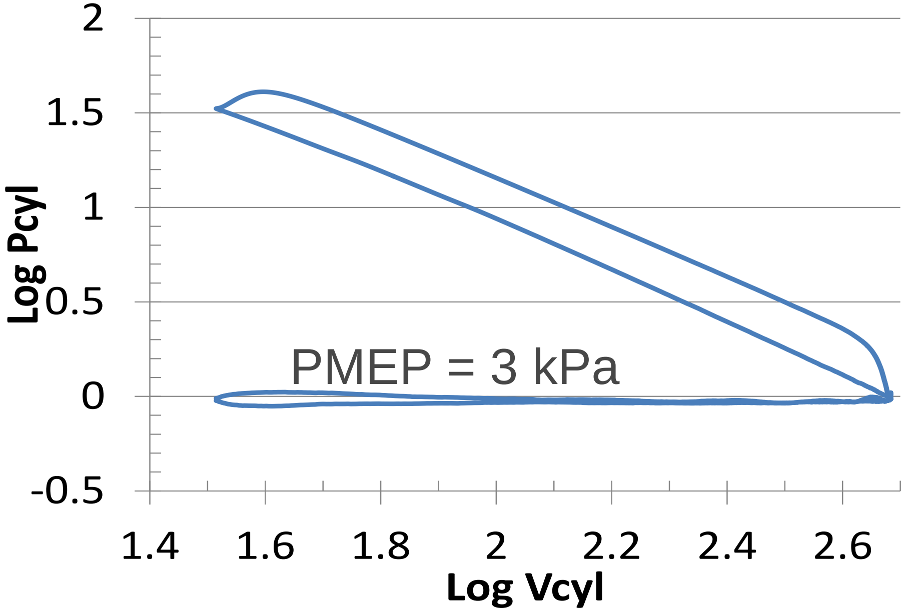
Typical Combustion (1000rpm-3bar IMEP)

- Single Injection with exhaust rebreathing (SOI=40 btdc)
- Start-of-Combustion near TDC
- Low PMEP – rebreathing during intake stroke
- Stable, low-temperature combustion with good Texh

Measured Pcyl and Heat Release



PV Diagram



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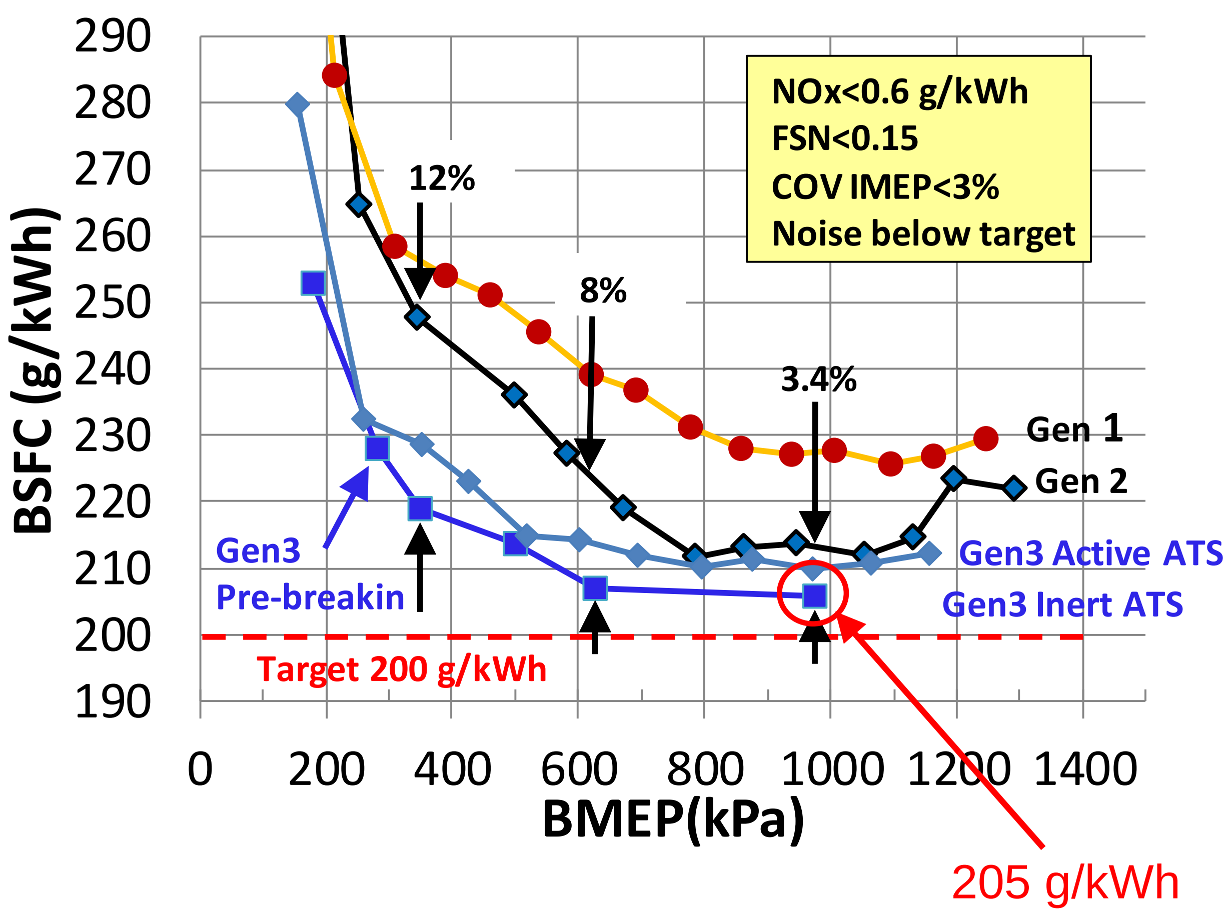
BSFC - 1500 rpm Load Sweep

- BSFC significantly improved relative to Gen1 and Gen2 engines
- Low BSFC over a wide load range where the vehicle operates on drive cycle
- Near target: 200 g/kWh (~42% brake thermal efficiency)
- Exceptional light-load BSFC
- Small BSFC difference (~2%) attributed to aftertreatment system, which oxidizes unburned fuel prior to LP EGR system



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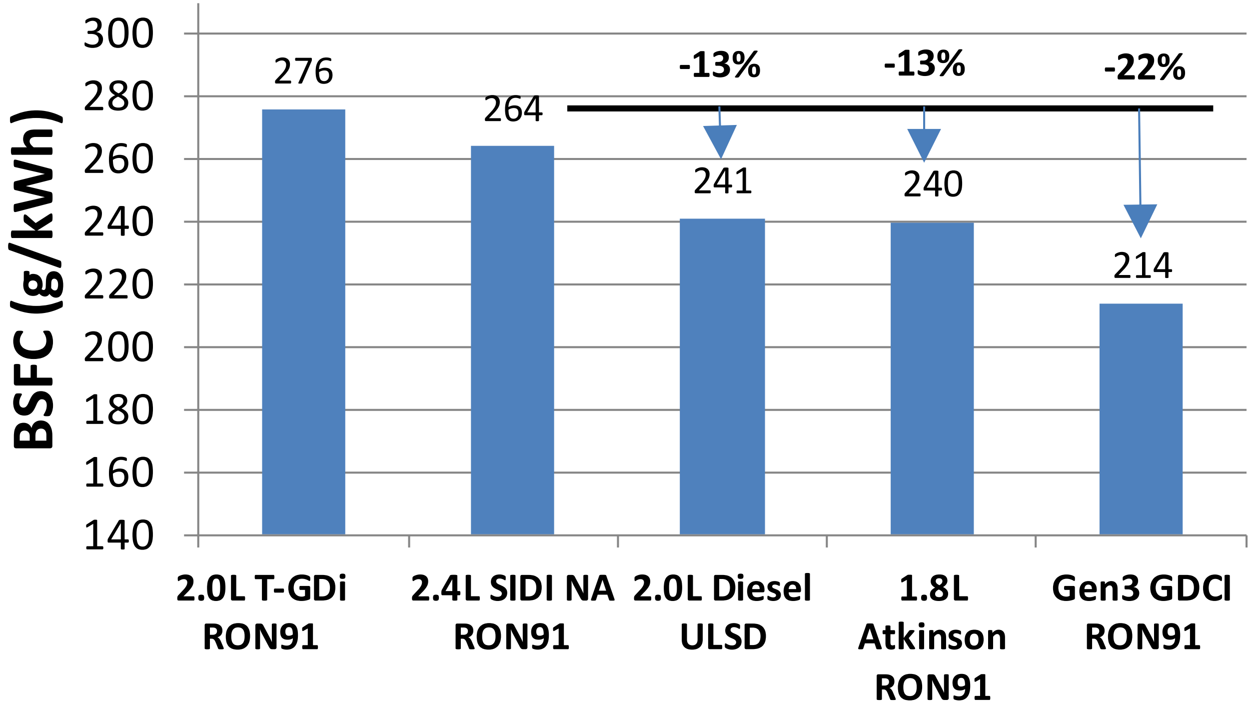
BSFC Benchmarking: 1500rpm-6bar IMEP

- GDCI is approx. 22% more efficient than SIDI turbo engine
- Approx. 11% more efficient than a leading 2.0L EU diesel
- Approx. 11% more efficient than 1.8L Atkinson engine (3rd Gen. Prius)



GDCI has excellent part-load fuel economy relative to class leading turbo SI and diesel engines

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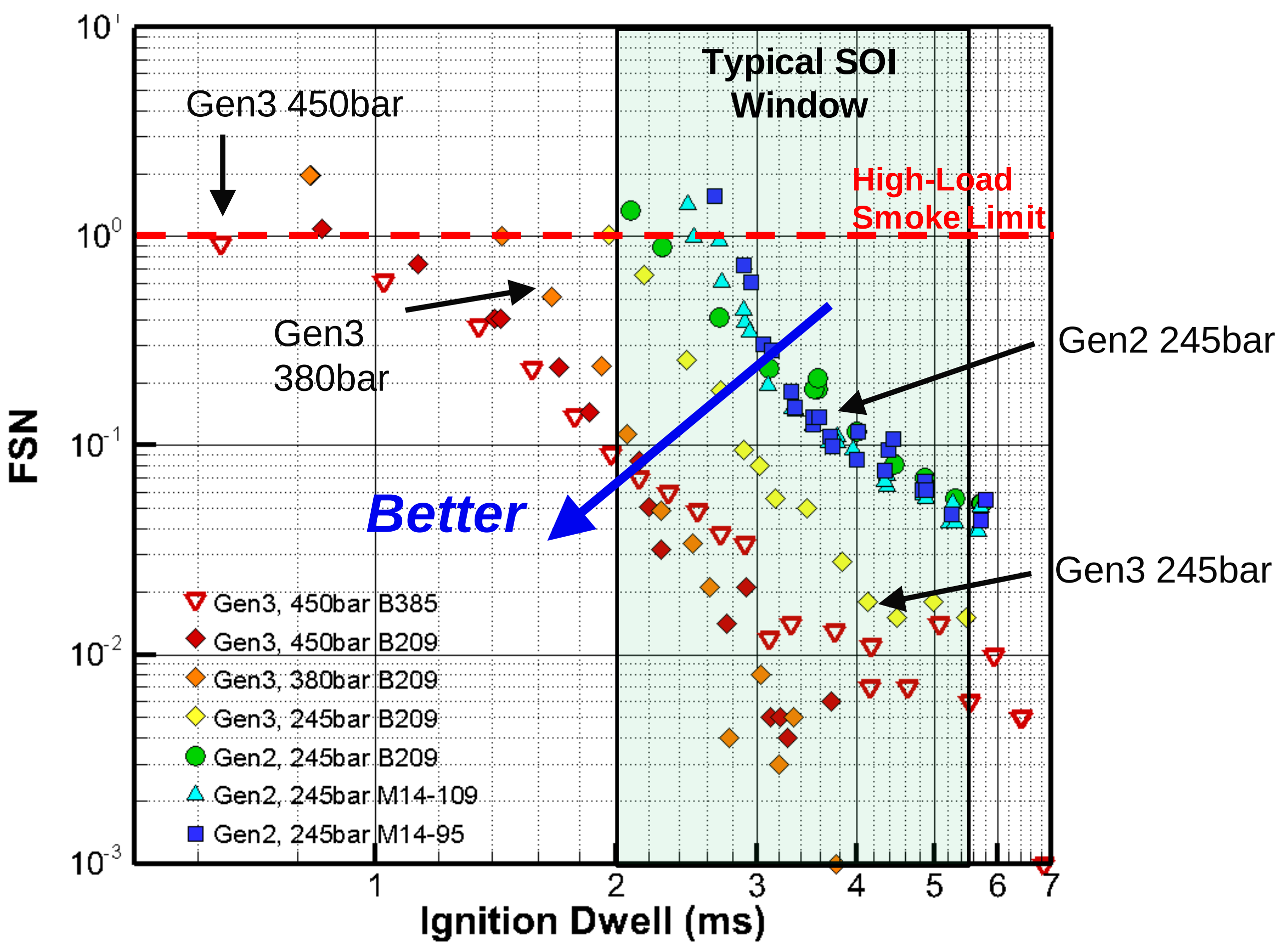
Reduced Smoke Emissions - 1500 rpm-11bar IMEP

- Smoke characteristic typically depends on injection timing
- Gen3 combustion system exhibits greatly reduced smoke
  - Attributed to "wetless" combustion system
- Strong injection pressure dependency for Gen3
  - Enables GDCI late injection with low smoke
- Further smoke reduction expected with latest injectors and sprays



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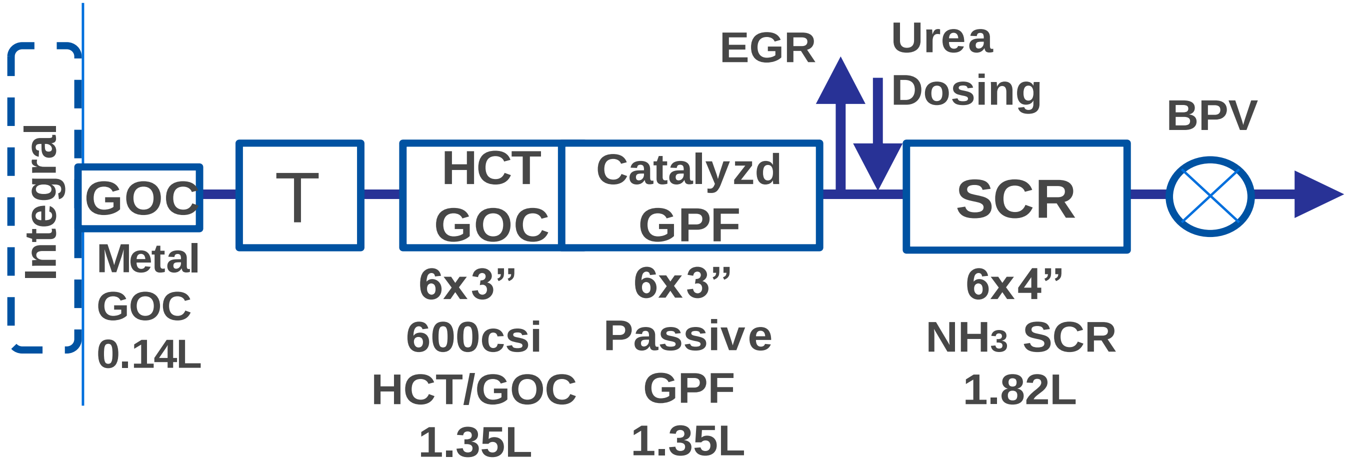
Emissions Challenges for Low-Temp Comb.

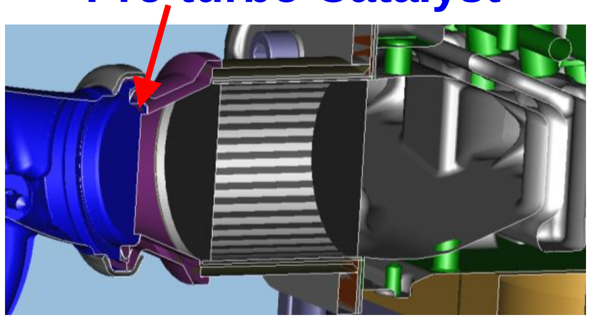
- Very challenging to achieve Tier3-Bin30 with low-temp combustion
- Low-temperature combustion equates to low-temp exhaust
- Engine out NOx and smoke are very low; HC and CO are SI-like
- Commercially viable technology must achieve very low TP emissions both on-cycle and off-cycle including high load.
- Clean EGR flows are imperative for good engine health (sticky components, compressor degradation, cooler fouling)

Gen3 Aftertreatment System (ATS) for Tier3- Bin30

- Heat conservation: compact, integral, air-gap insulated, exh. manifold
- <u>HC/CO</u>: Pre-turbo Cat w fast lightoff, HC Trap, GOC
- <u>Particulates</u>: catalyzed, passive GPF for off-cycle
- EGR feed stream post GPF
- <u>NOx</u>: close-coupled SCR system with urea evaporator



Pre-turbo Catalyst



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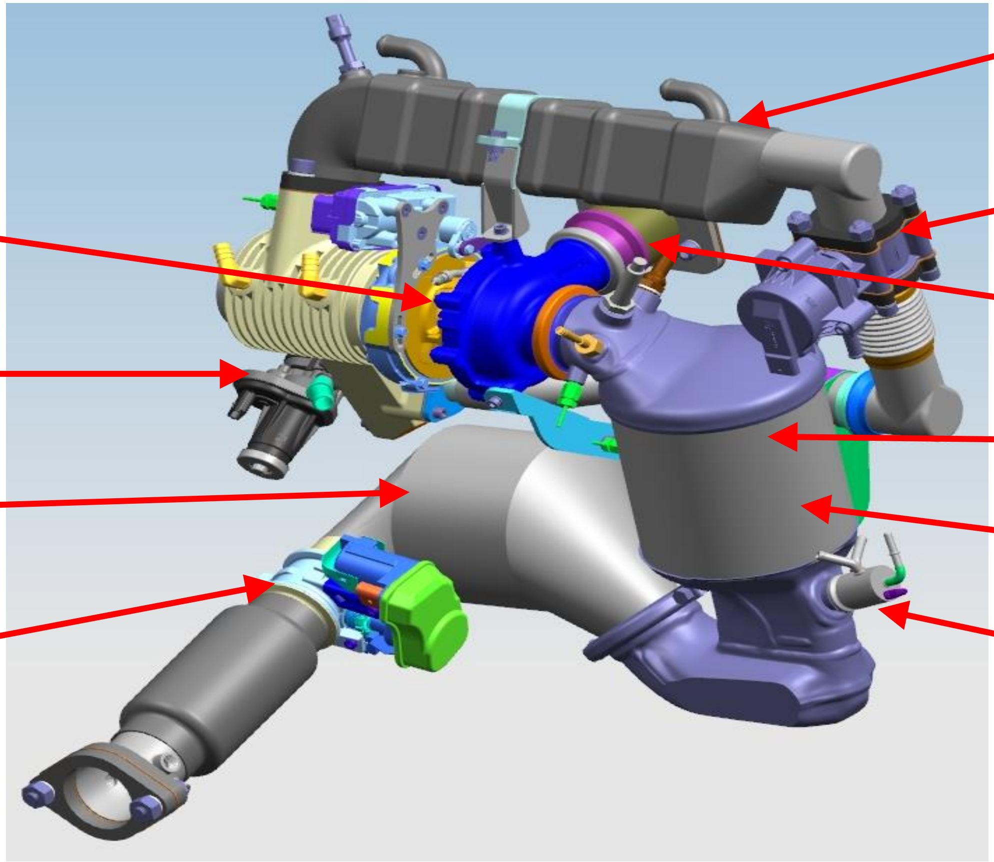
Packaging: Gen3 Aftertreatment for T3B30

- Packaging is very compact for D-class passenger car
- Emphasis on heat conservation, short ducts, low space velocities
- Using Daimler SCR evaporator – good urea mixing and SCR temps



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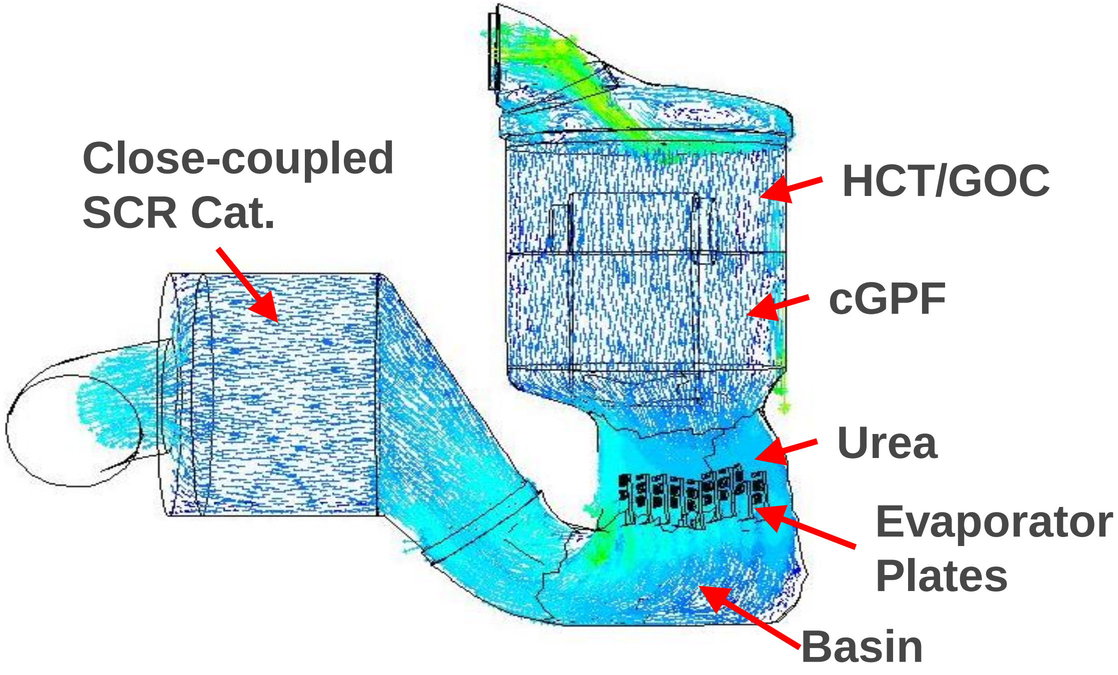
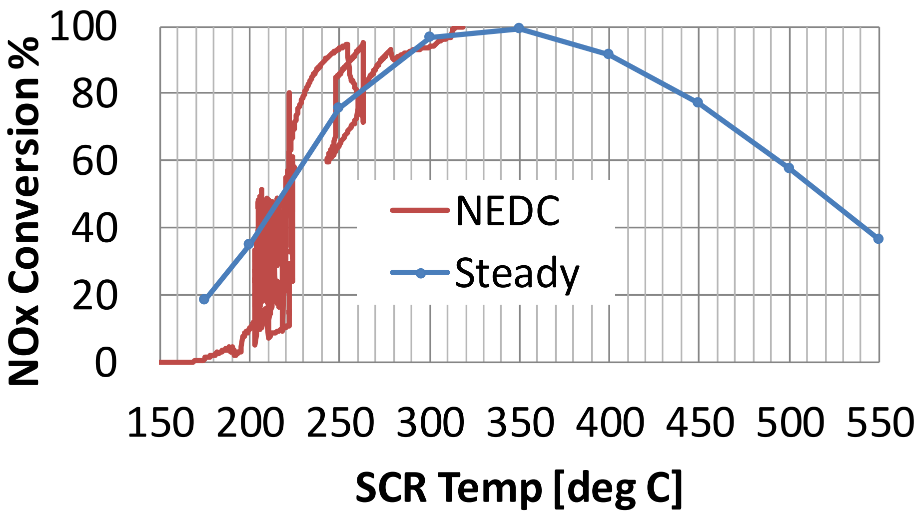
Close-Coupled SCR System (Gen3 GDCI)

- 3D & 1D simulations used to develop dosing strategies
- 300 C needed for high NOx conversion efficiency
- Tier3-Bin30 NOx target may be achievable depending on light-off strategy
  - Testing needed

3D Simulation – Urea Dosing



1D Simulation – NOx Conversion



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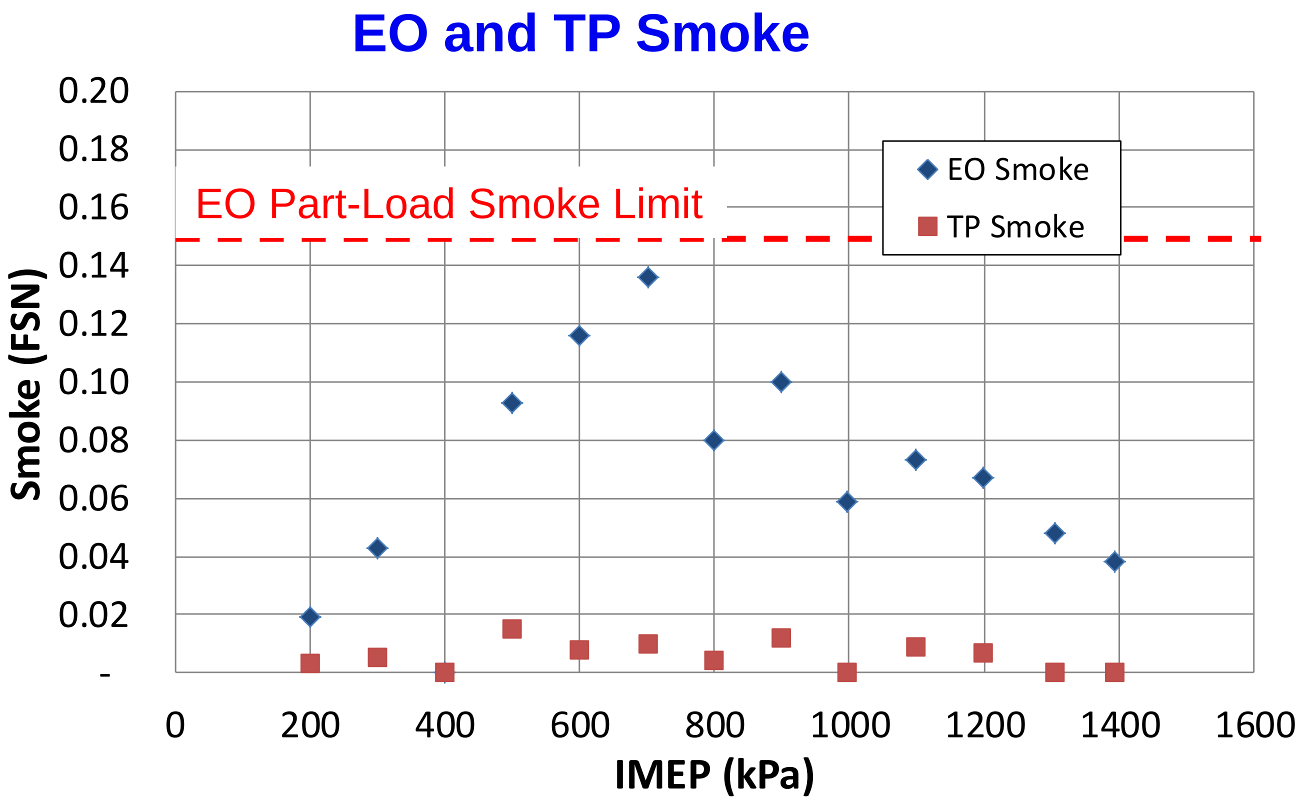
Smoke Emissions – 1500rpm Load Sweep

- Low engine out (EO) smoke over low-to-medium loads
- A small gasoline particulate filter (GPF) exhibits high trapping efficiency (1.35L)
- TP smoke <0.02 over load range
- Testing planned to characterize particle size and number
- Overall, very good trapping efficiency for small particles.



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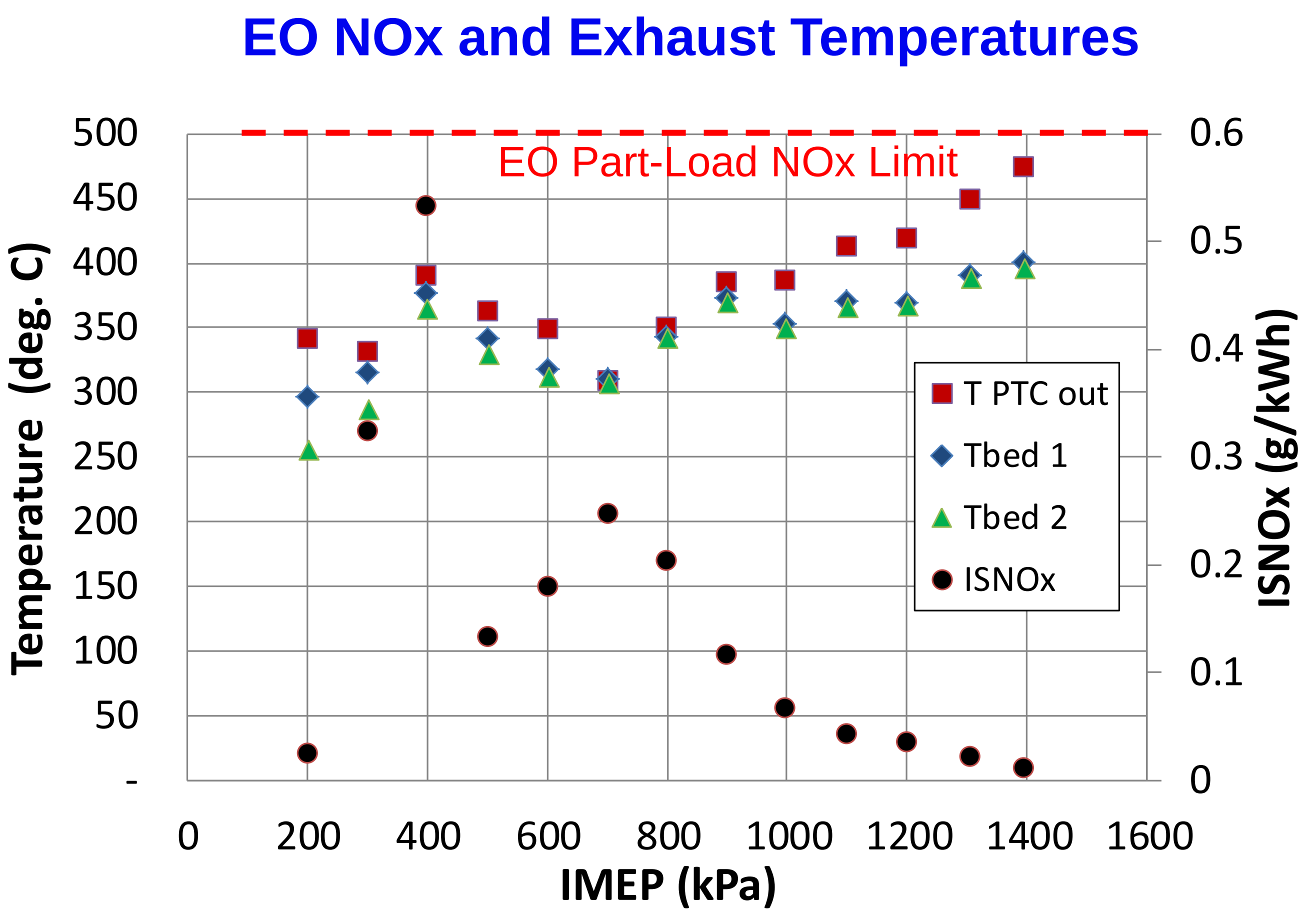
NOx and Exhaust Temp. – 1500rpm Load Sweep

- Low EO NOx over low-to-medium load range (<0.6 g/kWh limit)
- SCR temp exceeds the critical 300 C at most operating conditions for high NOx conv. efficiency.
  - SCR testing not yet completed
- Texh at PTC and GOC exceeds 300 C, even at low loads
- Texh increases with load; expected maximum <500 C.



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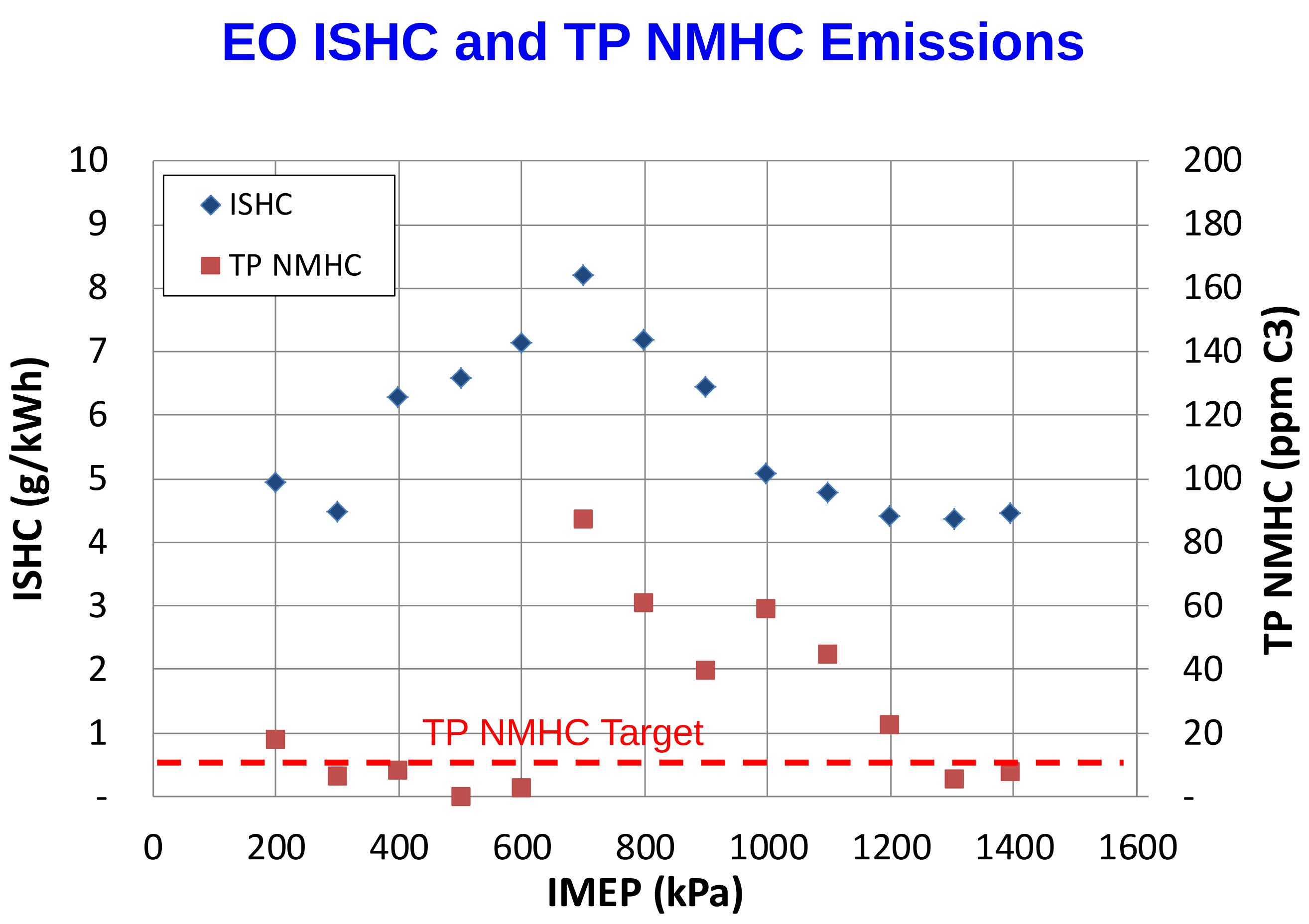
EO and TP HC Emissions – 1500rpm Load Sweep

- Reasonable EO HC over low-to-medium load range
- TP NMHC are below target (10 ppm) at light-to-moderate loads; increasing above targets at higher loads
- Future tests:
  - Low-temp. oxidation catalyst
  - Cold start tests



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Summary – Gen3 GDCI

- GDCI technology is evolving with very stringent requirements for fuel efficiency, CO2 emissions, and criteria emissions.
- Preliminary dynamometer tests show:
  - BSFC ~205 g/kWh for a wide load range
  - Smoke was greatly reduced, especially for late SOI (“wetless” injection process)
- While very challenging, preliminary Texh & emissions data indicate good potential to meet Tier3-Bin30 targets
- More testing and engine calibration is needed ahead of vehicle implementation

Acknowledgements

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Questions?