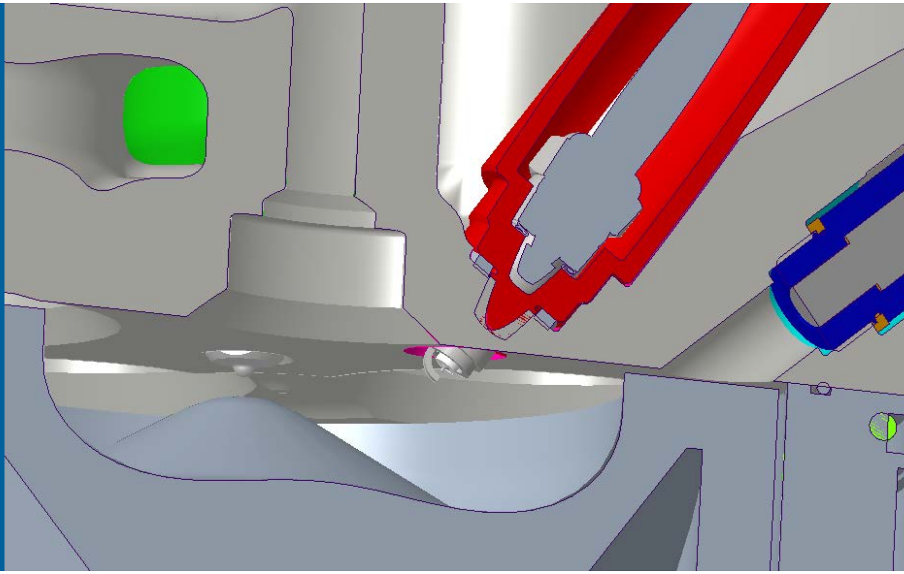
Project ID# ACE132



HEAVY-DUTY GASOLINE COMPRESSION IGNITION

CHRISTOPHER KOLODZIEJ, HEE JE SEONG, JORGE PULPEIRO GONZALEZ, MICHAEL PAMMINGER, BUYU WANG, DOUG LONGMAN

2019 DOE Vehicle Technologies Office Annual Merit Review
Advanced Combustion Engines
9:30 AM, June 13, 2019

DOE Vehicle Technologies Office Management:
Michael Weismiller & Gurpreet Singh

OVERVIEW

Timeline

- Started Oct 2018
- End date Sept 2021
  - Lab Call reset Oct 2018
- 16% Completed

Barriers

- Reduced heat loss
- Lower engine-out emissions
- Expand Low Temperature Combustion (LTC) operation
- Robust cold start and low load for HD GCI

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in:
  - FY19 (new) $950k

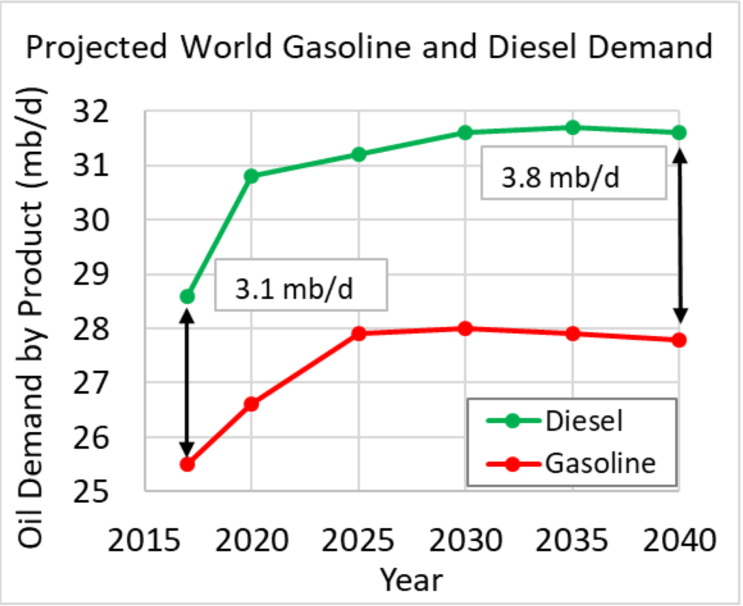
Partners

- Caterpillar
  - Engine head modifications
  - Common rail injection equipment

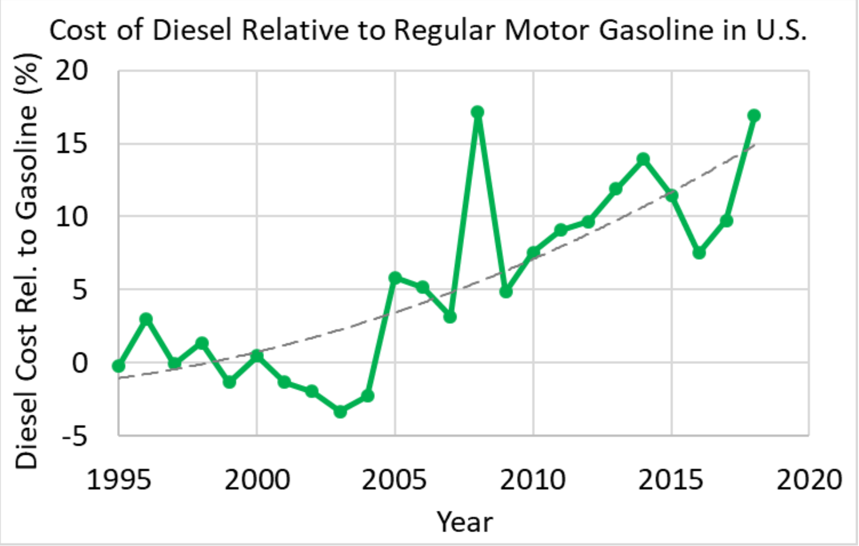
RELEVANCE/OBJECTIVES

Energy Security and Economic Vitality:

- Diesel is the main fuel of MD/HD engines
- Projections show that world-wide diesel demand will grow faster than gasoline
- In the US, the cost of on-highway diesel fuel has been increasing consistently relative to regular grade gasoline
- However, current gasoline spark-ignition (SI) engines do not satisfy the efficiency and load requirements of the MD/HD fleet



Gasoline Compression Ignition (GCI) engines offer high efficiency fuel flexibility to the MD/HD fleet



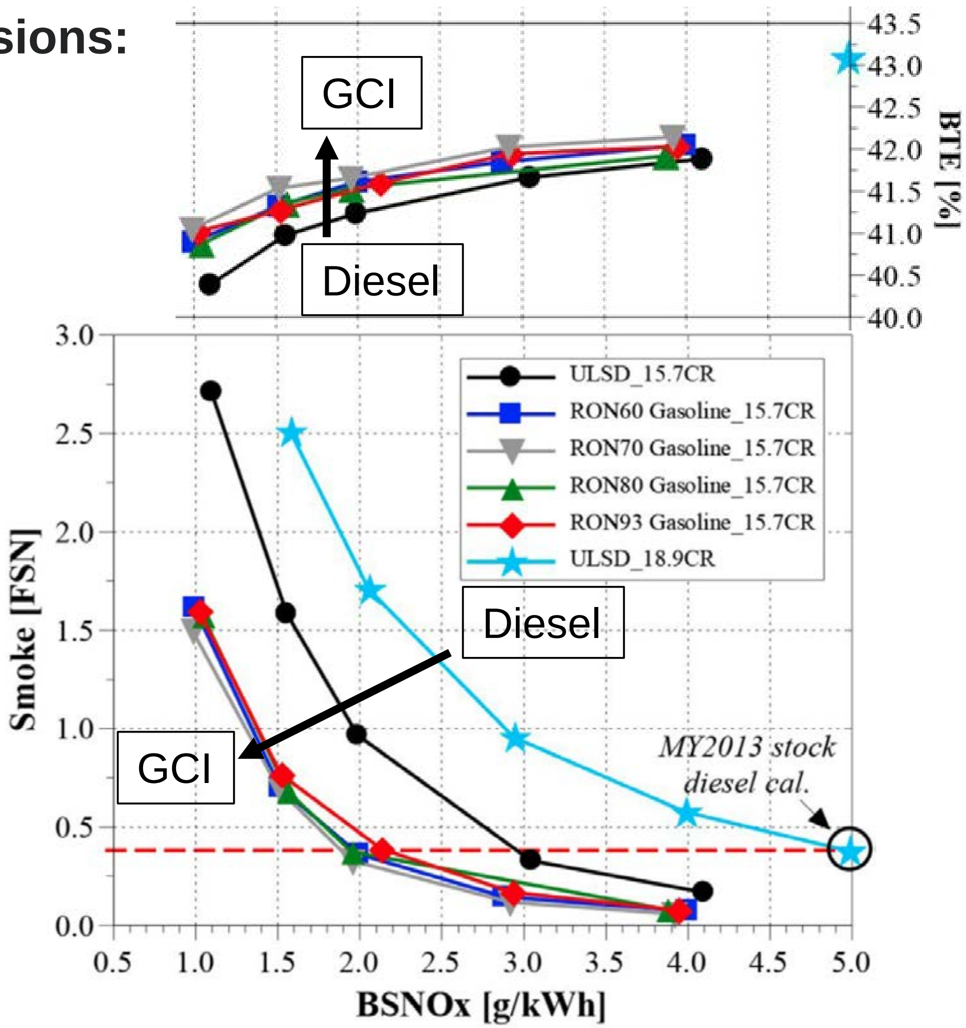
Ref. 2018 OPEC World Oil Outlook
Ref. U.S. EIA April 2019 Monthly Energy Review

RELEVANCE/OBJECTIVES

Increased Efficiency and Lower Emissions:

- Diesel-like efficiency
- 50% smoke reduction at same BSNOx

Gasoline Compression Ignition (GCI) has the potential for high diesel-like efficiency and reduced emissions.



14.9 L HD Engine. 1375 RPM, 10 bar BMEP.
CA50 = 6 ºaTDC

Ref. Zhang, Y, et al., SAE 2018-01-0226

RELEVANCE/OBJECTIVES

1. Obtain the most efficient use of gasoline in a HD engine through compression ignition
   a. Reduced heat losses
   b. Combustion chamber (piston) design
   c. Injector design and injection parameters
2. Reduce engine-out PM and NOx emissions relative to diesel combustion
   a. Minimize total fluid consumption (fuel and DEF) and total cost of ownership
   b. Identify and avoid conditions of liquid spray impingement
   c. Injection parameters to reduce engine-out soot emissions and number of active particulate filter regenerations
      a. With the wide range of off-road duty cycles, this could have high significance.
3. Identify robust cold start and low load approaches
   a. Compare spark ignition, spark assisted compression ignition, and compression ignition in a large bore quiescent HD combustion chamber
   b. Fast aftertreatment warm-up

RESOURCES

- Caterpillar Single-Cylinder Oil Test Engine (SCOTE)
  - 2.4 L Displacement
  - 16.2:1 Compression Ratio

Currently	Being Installed
SCOTE Head with HEUI, Endoscope, and Cyl. Press. Transducer	SCOTE Head with Common Rail Injector, Spark Plug, and Cyl. Press. Transducer
Hydraulic Electronic Unit Inj. (HEUI) System	Stand-alone Common Rail Pump System
Absorption-only DC Dyno	AVL Motoring AC Dyno
AVL Fuel Balance	Resol Coriolis Meter and Fuel Conditioning
Caterpillar ECU	Vieletech LabVIEW Controls/Data Acq.
	Cylinder Fast-Sampling Valve

- Existing Equipment:
  - Port Fuel Injection (PFI), AVL Visioscope, AVL FT-IR, Dekati FPS-4000 Diluter, TSI SMPS

RESOURCES

Heavy-Duty Gasoline Compression Ignition Engine Research for Off-Road Vehicles

Task	Name	FY19 Funding
1	HD Off-Road Industry Workshop	$50k
2	Heavy-Duty Gasoline Compression Ignition	$600k
3	Ultra-fast sampling system for in-cylinder, crank resolved emissions.	$300k
Total		**$950k**

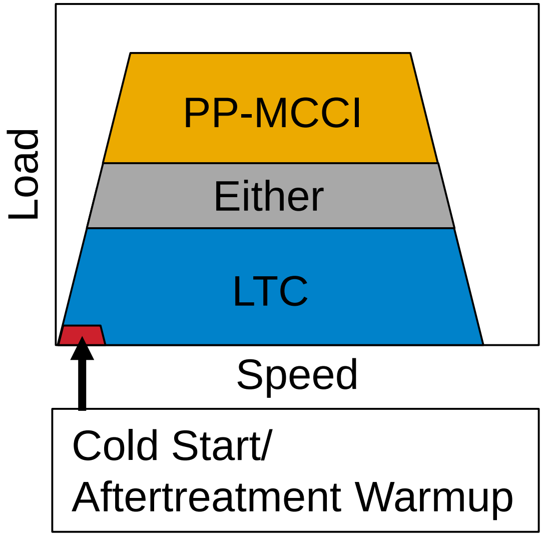
MILESTONES

Quarter	Milestone	Status
FY19-Q1	Upgrades to engine and test cell for single-cylinder HD GCI research. Baseline on diesel fuel.	Postponed to Q4
FY19-Q2	Single-cylinder HD GCI combustion and emissions baseline on gasoline fuel.	Postponed to Q1 FY20
F19-Q2	Complete parametric study of fast sampling valve from a high-pressure chamber.	Postponed to Q3
F19-Q3	Identify cylinder densities and injection conditions where fuel impingement occurs.	On Track
FY19-Q4	Install fast sampling valve in engine cylinder head.	On Track
FY20-Q2	Define load ranges for LTC and PP-MCCI with initial CR.	On Track
FY20-Q4	Investigate required cylinder conditions for cold start and examine gaseous and particulate formation processes.	On Track

APPROACH

Use gasoline-like fuels for reduced emissions, increased efficiency, and efficient HD engine fuel flexibility.

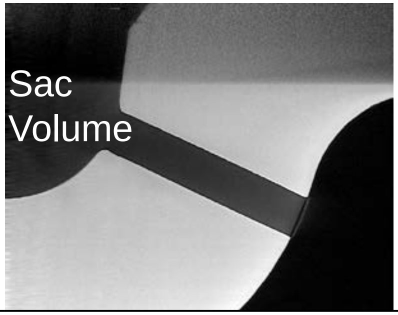
- High Load
  - Use partially-premixed mixing-controlled compression ignition (PP-MCCI) for robust combustion phasing control
  - Minimize heat loss and particulate emissions
  - Investigate injection parameters and injector design
  - Find the minimum operable load for MCCI combustion
- Moderate Load
  - Area where engine could operate in PP-MCCI or Low Temperature Combustion (LTC)
  - Identify trade-offs between these two combustion modes
- Low Load
  - Use LTC for highest efficiency and lowest particulate and NOx emissions, but manage combustion noise and HC/CO emissions
  - Use spray modeling to avoid any liquid impingement
- Cold-Start/Aftertreatment Warmup
  - Compare combustion modes at idle in a quiescent large bore HD engine (Stoichiometric SI, SACI, CI)
  - Develop approaches to transition between modes



APPROACH

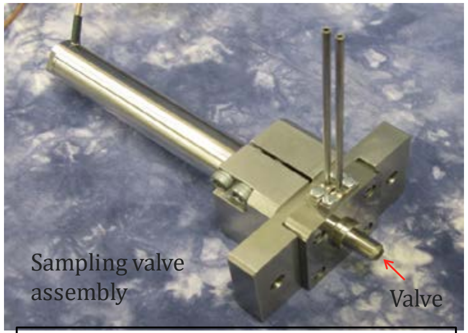
Use advanced tools to better understand processes of injection, sprays, combustion, and emissions.

- Use x-ray tomography to monitor injector cavitation erosion with gasoline
- 1D/3D spray simulations to identify conditions of liquid length impingement
  - Test 120°, 130°, and 150° inclusion angle nozzles
- Endoscopic imaging of soot radiation/pool fires
- Cylinder fast sampling valve to characterize soot formation and oxidation processes
- Particle size distribution and TEM morphology



*X-ray image of new CAT injector tip (Powell et al.)

Endoscopic imaging



Fast Sampling Valve

TECHNICAL ACCOMPLISHMENTS & PROGRESS

TEST CELL UPGRADES

- AVL motoring dynamometer
  - Arrived April, 2019
  - To be commissioned July, 2019
- Resol low pressure fuel supply and measurement
  - Moved from previous GCI test cell
- Common rail high pressure fuel unit
  - Being converted for safe operation with gasoline
    - New explosion-proof electric motor
    - 480V variable speed drive relocation
- Vieletech (formerly Drivven) LabVIEW same/next-cycle controller and full test cell data acquisition
  - To be commissioned after dynamometer

Full test cell recommissioning expected: September, 2019

Source: https://www.avl.com/load-unit-for-engine-testing

Source: http://www.ni.com/en-us/support/model.dcm-2301.html

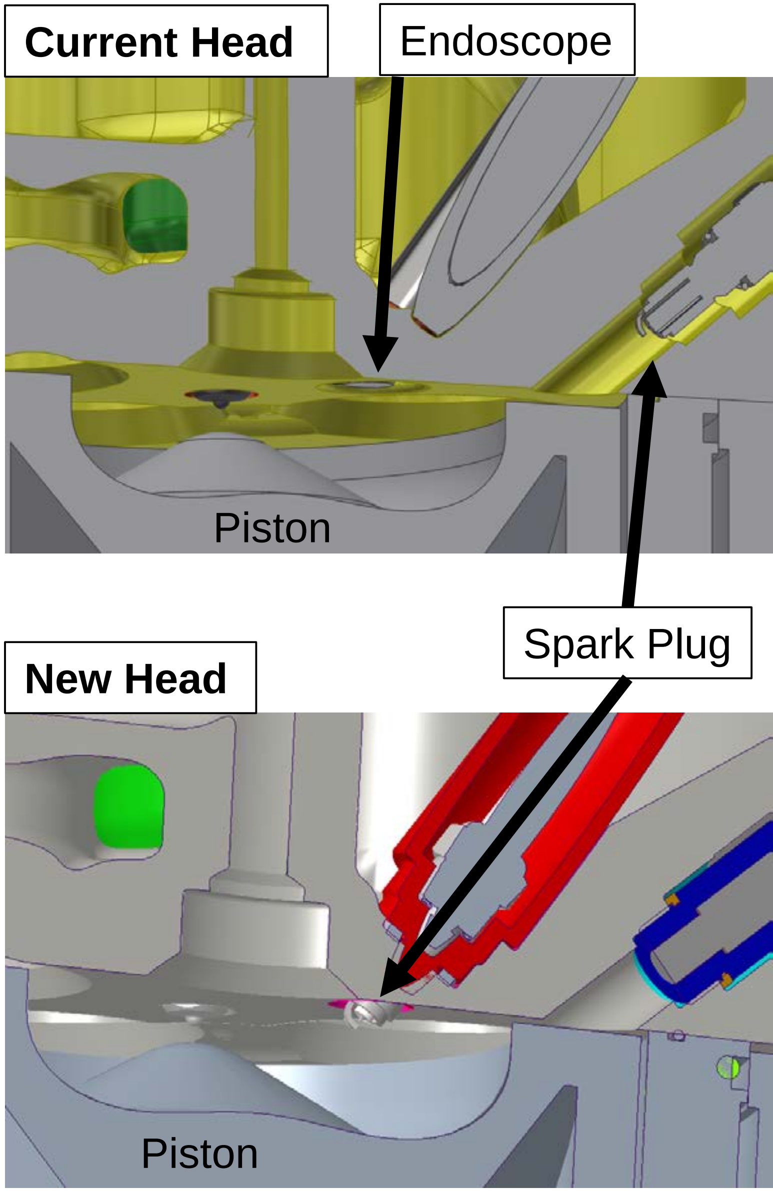
CATERPILLAR CYLINDER HEAD MODIFICATIONS

Current Cylinder Head:

- Originally modified to work with CAT HEUI
- CAT designed modifications for common rail
- Endoscope port previously existed
- M8 spark plug inserted into non-ideal location (unused pressure relief port)
  - Located in squish region
  - Significant recession

New Cylinder Head:

- Spark plug adapter in place of endoscope
  - Inside the piston bowl
- Cylinder pressure transducer in pressure relief port, common location
- Injector bore modified for common rail injector



INITIAL PORT FUEL INJECTION (PFI) SPARK IGNITION (SI) TESTING

Objectives:

- Identify range of spark timings between knock and combustion stability limits

Constraints:

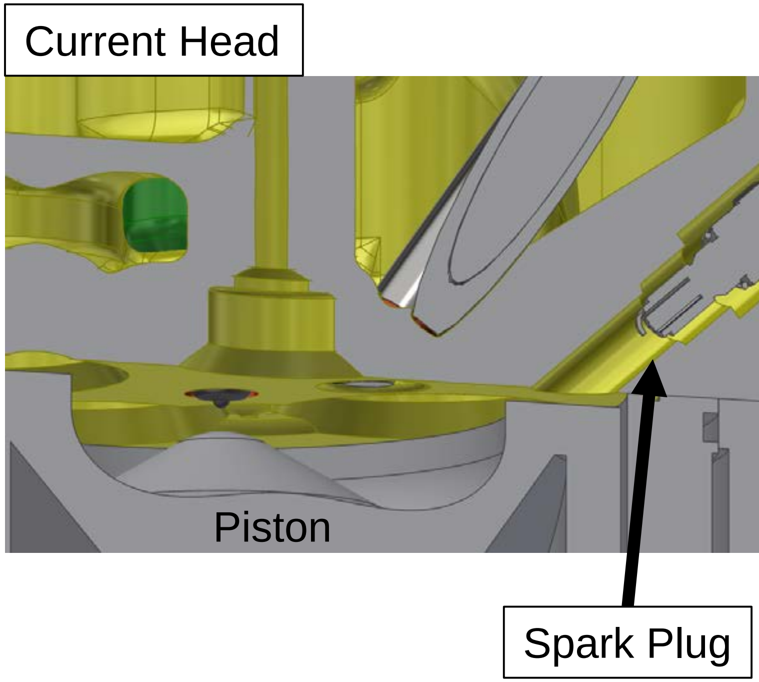
- Low swirl, turbulence, and flame speed
- Large bore for flame to propagate across
- Spark plug recessed above squish
- High 16.2:1 CR

Test Limits:

- 0.75 bar Maximum Amplitude of Pressure Oscillations (MAPO)
- 3% COV of IMEP combustion stability limit

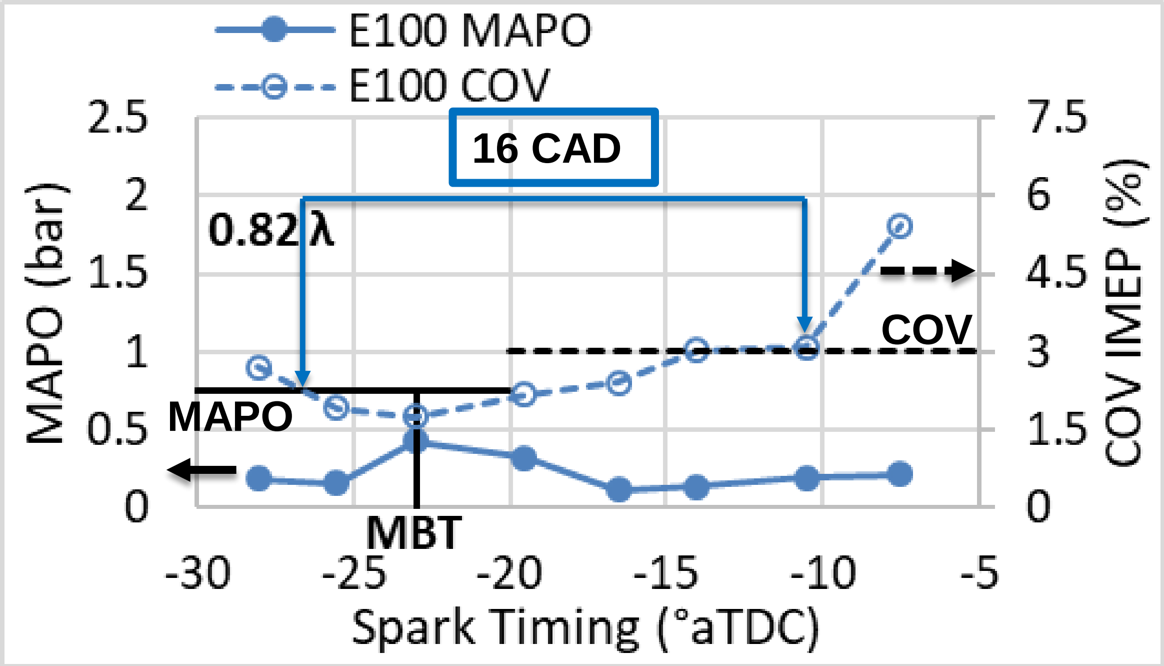
Fuels Investigated:

- E100 (100% Ethanol)
  - High flame speed
  - High knock resistance
- E10 gasoline (87 AKI)



MAXIMUM SOI RANGE

- 750 RPM, 3.2 bar IMEPg
- -23 °aTDC MBT spark timing
  - Without end-gas autoignition
- E100 not knock limited at **0.82 λ**



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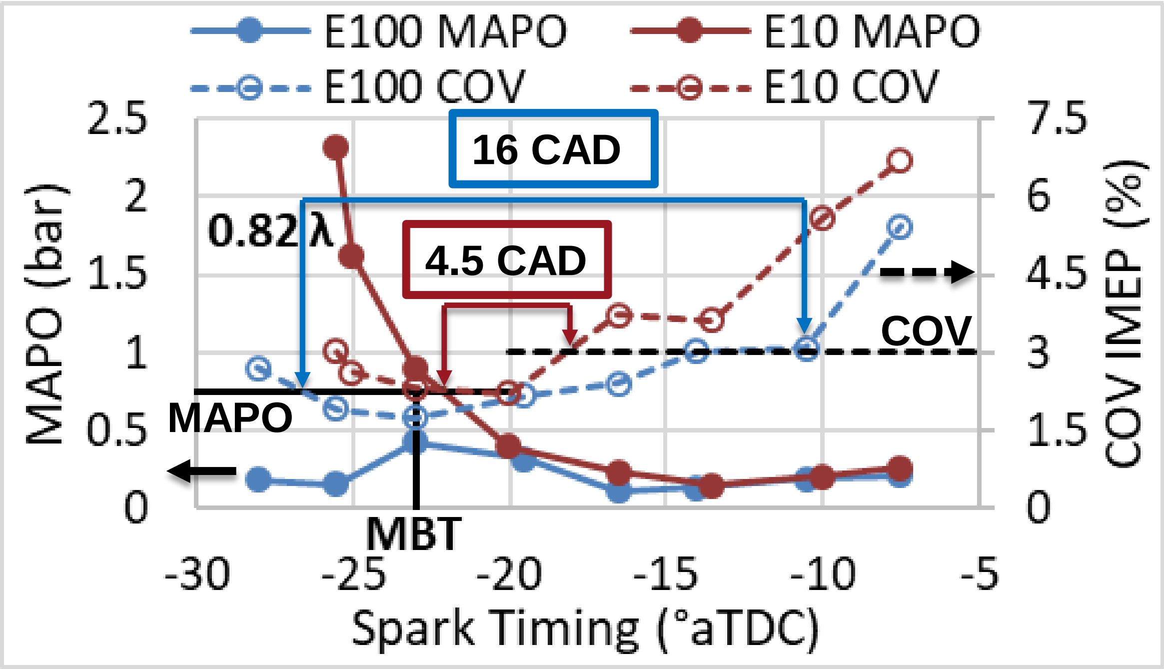

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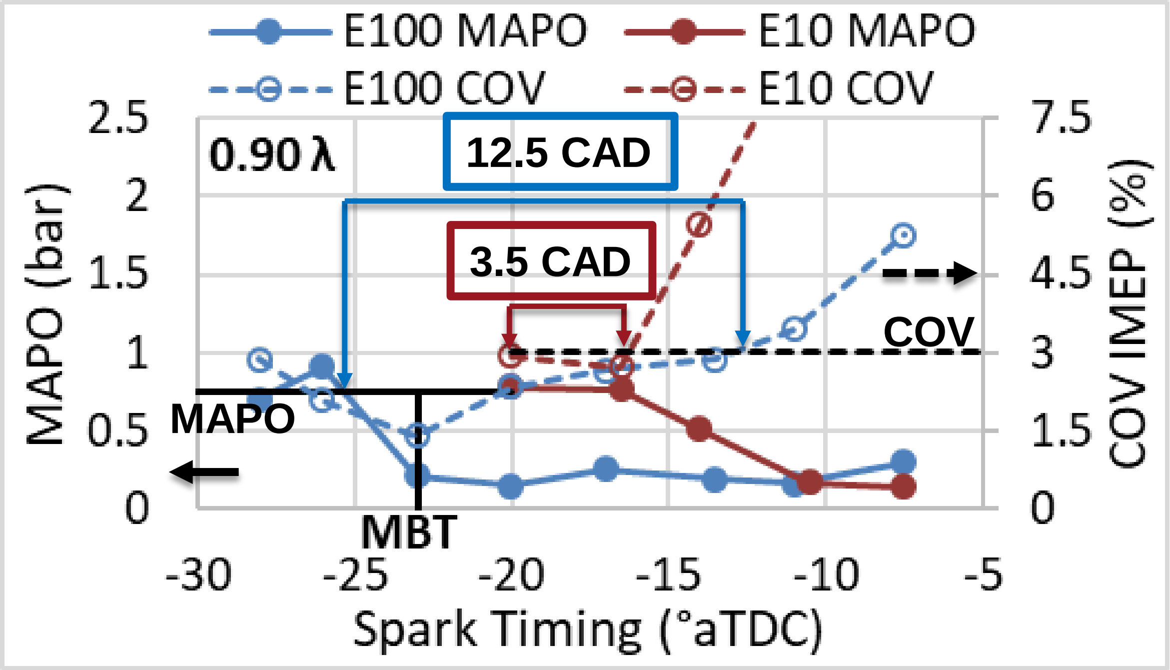
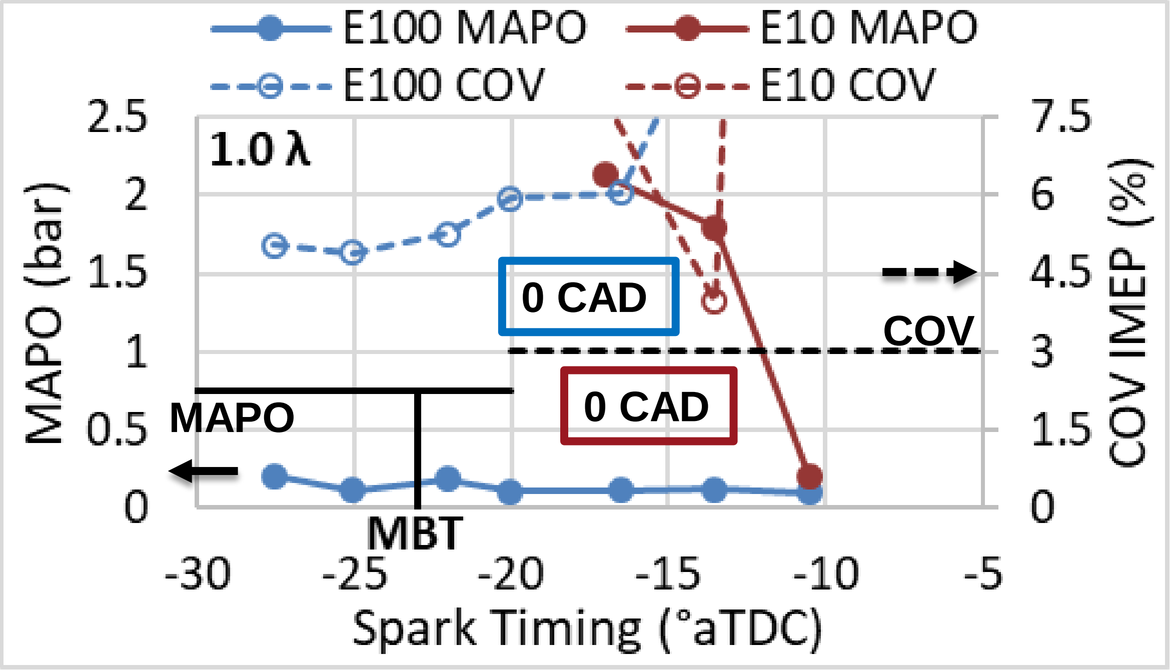
MAXIMUM SOI RANGE

- 750 RPM, 3.2 bar IMEPg
- -23 °aTDC MBT spark timing
  - Without end-gas autoignition
- E100 is knock limited at **0.90 λ**



MAXIMUM SOI RANGE

- 750 RPM, 3.2 bar IMEPg
- -23 °aTDC MBT spark timing
  - Without end-gas autoignition
- E100 not knock limited at **1.0 λ**

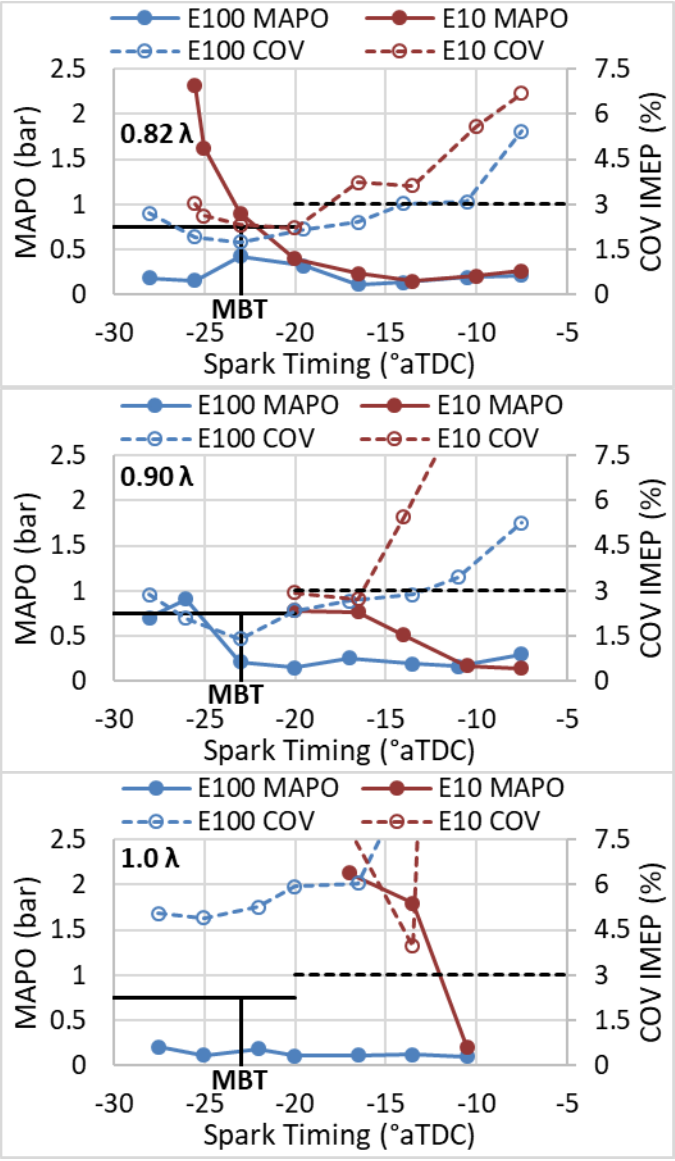


MAXIMUM SOI RANGE

- 750 RPM, 3.2 bar IMEPg
- -23 °aTDC MBT spark timing
  - Without end-gas autoignition

Fuel	λ	SOI Range
E100 E10	0.82	16 CAD 4.5 CAD
E100 E10	0.90	12.5 CAD 3.5 CAD
E100 E10	1.00	0 CAD 0 CAD

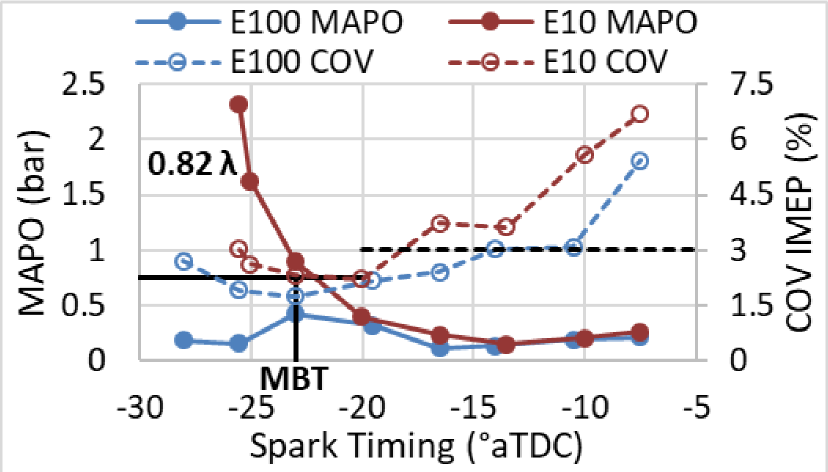
E100 at 0.82 λ allowed for the widest spark timing range from a combination of higher knock resistance (earlier ST limit) and laminar flame speed (later ST limit).

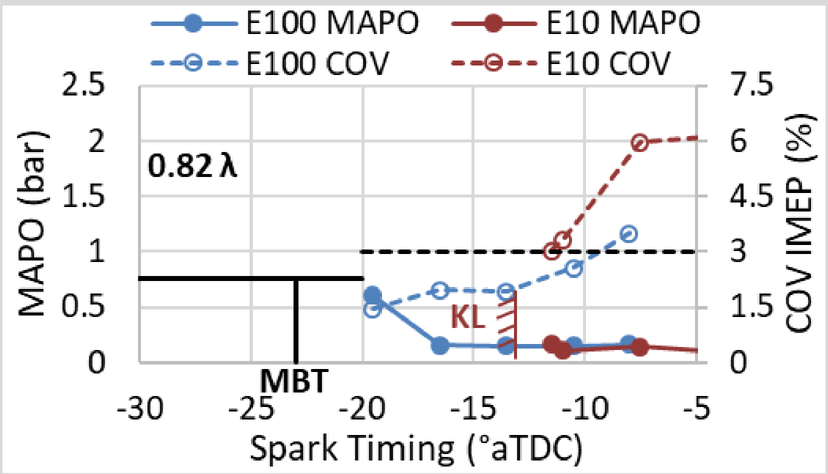


EFFECTS OF ENGINE LOAD

- 3.2 bar vs. 3.8 bar IMEPg
- Operable range shifted later
- MBT was knock limited (E10 & E100)
- Later ST at higher fueling allowed increased exhaust enthalpy

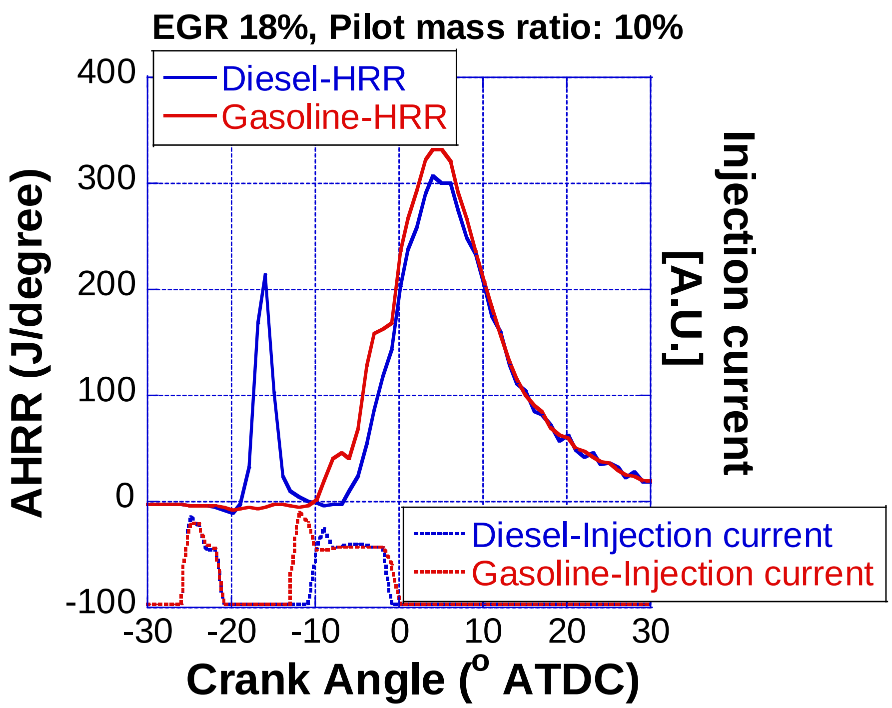
Fuel	λ	IMEPg	SOI Range
E100 E10	0.82	3.2 bar	16 CAD 4.5 CAD
E100 E10	0.82	3.8 bar	11 CAD <3 CAD





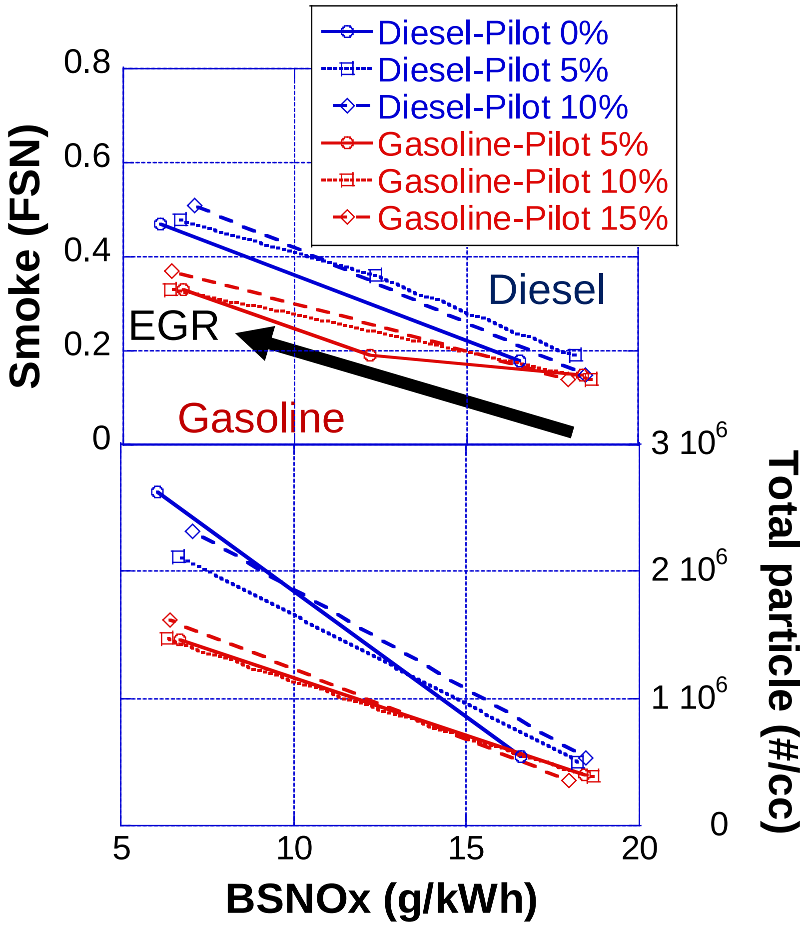
DIESEL VS. GASOLINE PARTICULATE CHARACTERIZATION AT HIGH LOAD

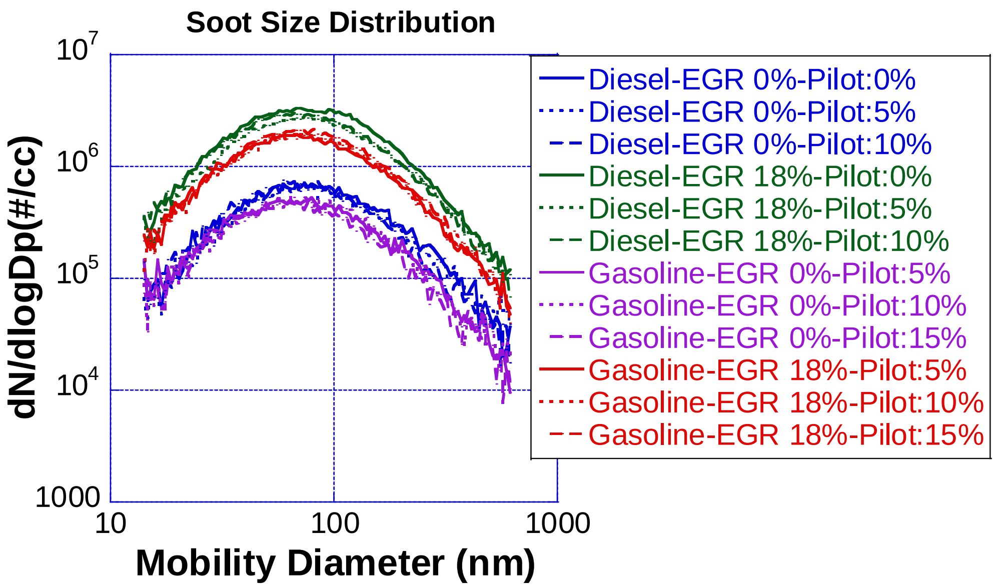
Parameter	Value
Navistar 12.4L 6-cylinder (CR 17:1)	
Engine Speed [rpm]	**1038**
Engine Load [bar BMEP]	**14.1**
CA50 [°aTDC]	**6.3 ± .4**
Fuel	ULSD & Tier II EEE
Start of Injection [°aTDC]	-27.5/-14.5~-12 (varied)
Pilot mass ratio (%)	0, 5, 10 & 15
EGR [%]	0, 9 & 18



- Methodology: Hold constant CA50 by varying SOI_2
- Observations:
  - Longer ignition delay of pilot fuel injection with gasoline
  - EGR impact (0-18%) on combustion was minor for the same fuel

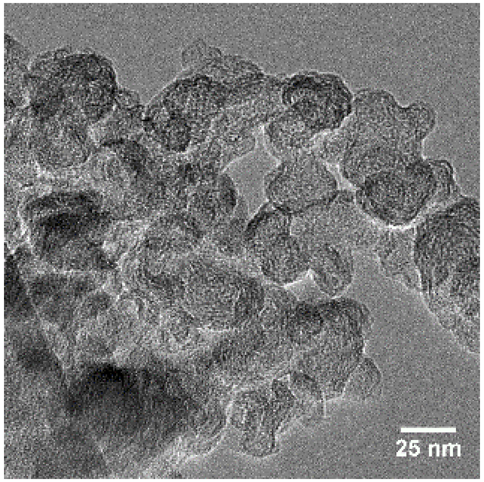
GASOLINE REDUCED THE SOOT-NO_X TRADE-OFF



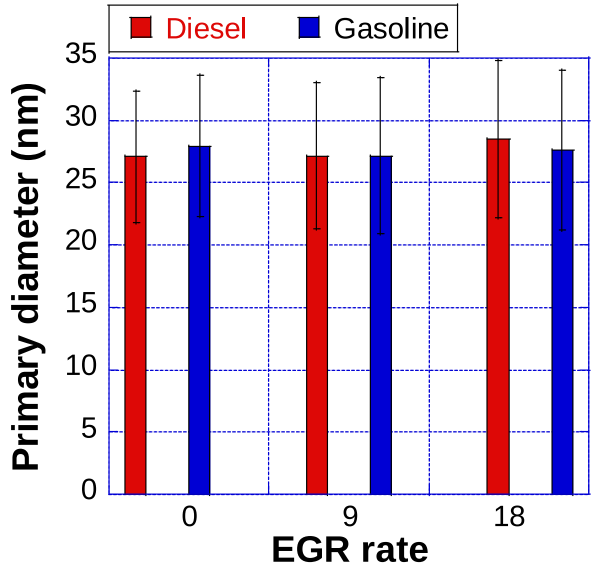


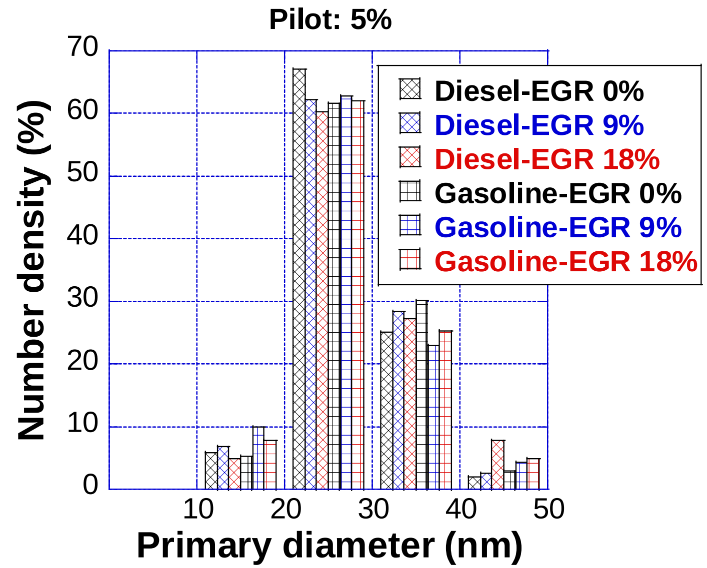
- Lower Soot-NO_x trade-off with gasoline
- Similar shaped size distributions for both fuels
  - But fewer particles with gasoline

TEM & RAMAN PARTICULATE STRUCTURE ANALYSIS



Gasoline (EGR 0%, Pilot 5%)





- Transmitting Electron Microscope (TEM) analysis of soot primary particle size and distributions showed strong similarities between diesel and gasoline under high load (14 bar BMEP) MCCI combustion
- No significant effect for 0-18% EGR

- Raman analysis for carbon crystalline structure performed
  - In technical back-up slides
- Similar crystalline structures for both fuels with EGR

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RESPONSES TO 2018 AMR REVIEWER COMMENTS

Project# ACE132 “Heavy-Duty Gasoline Compression Ignition” is a new project for FY19 and was not reviewed last year.

COLLABORATIONS

Caterpillar (POC, Dr. Adam Dempsey)

- Engineering and hardware support

Clear Flame (Dr. Julie Blumreiter)

- Collaboration on PFI SI engine testing

ACE#010 (Powell, ANL)

- X-ray tomography of HD injector nozzle cavitation erosion with gasoline fuel

Navistar

- Diesel vs. GCI particulate characterization performed on Navistar Supertruck engine installed at ANL

Aramco Services Co.

- Discussions on HD GCI research

DOE VTO AEC Working Group

- CAT, Cummins, DDC, Mack, John Deere, GE, Navistar, Ford, GM, Chrysler, ExxonMobil, ConocoPhillips, Shell, Chevron, BP, ANL, SNL, LLNL, ORNL

REMAINING BARRIERS AND CHALLENGES

High Load:

- Reduced heat loss
- Reduced particulate and NOx engine-out emissions
- Increasing the premixed fuel fraction without exceeding combustion noise level limits

Low Load:

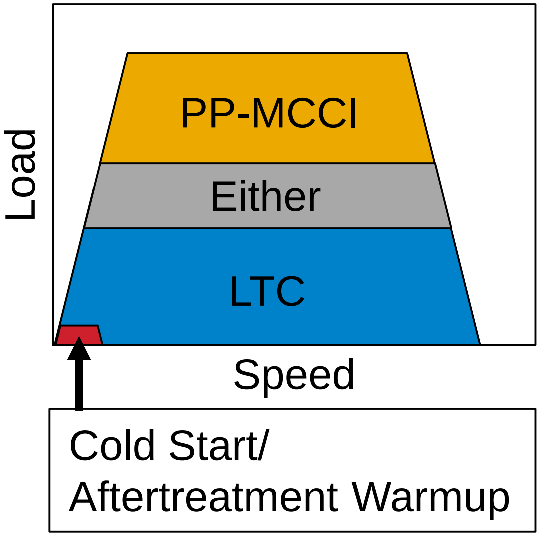
- Achieve robust LTC with higher efficiency and lower emissions than diesel combustion
- Avoid all liquid fuel spray impingement on the combustion chamber surfaces

Cold Start:

- Determine the most robust cold start approach that minimizes aftertreatment heating time

All Conditions:

- Characterize and mitigate cavitation erosion



PROPOSED FUTURE WORK

- Recommission test cell and convert engine from HEUI to common rail injection equipment
- Baseline engine on diesel fuel with guidance from Caterpillar
- Baseline GCI efficiency and emissions with initial injector and piston
- Evaluate improved low load ST range with spark plug location in the piston bowl
  - Vary depth of the spark plug protrusion
- Determine the cold start strategy with the highest exhaust enthalpy
- Use spray simulations to determine the conditions where impingement occurs
- Measure soot formation and oxidation processes using fast-sampling valve
- Record injector cavitation erosion from gasoline operation

Any proposed future work is subject to change based on funding levels.

SUMMARY

Relevance: HD GCI has lower emissions and diesel-like efficiency, while expanding the high efficiency fuel flexibility of the MD/HD fleet.

- Approach:
  - Operate a HD engine on gasoline with partially-premixed mixing-controlled compression ignition at high load and LTC at low load for lower emissions and higher efficiency
- Technical Accomplishment:
  - Modification to a production CAT SCOTE cylinder head to incorporate a spark plug
  - Initial PFI SI testing, with a non-ideal spark plug location, shows significant knock limitations for stoichiometric operation at ≈3 bar IMEPg with both E10 and E100
  - Despite different chemical composition, gasoline and diesel produced remarkably similar soot aggregate structures at high load with MCCI combustion
- Future Work:
  - Re-test low load PFI SI knock and combustion stability limitations with spark plug located in the piston bowl
  - Compare low load operation between SI and CI combustion
  - Implement a cylinder fast-sampling valve and detailed emissions characterization
  - Perform x-ray tomography imaging of injector nozzle to track cavitation erosion

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?