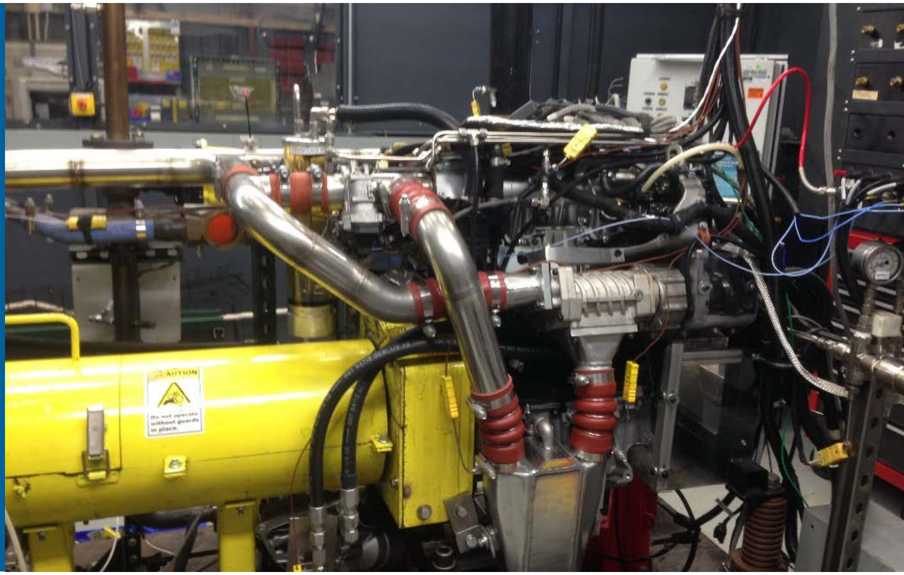
ADVANCES IN HIGH-EFFICIENCY GASOLINE COMPRESSION IGNITION



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FY16 DOE VT Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
1:45 – 2:15 PM, Wednesday, June 8, 2016

Project ID# ACE11

OVERVIEW

Timeline

- Started May 2008
- Reviewed as part of FY17 VTO Lab Call

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY15 $550k
  - FY16 $500k

Barriers

- From MYPP
  - Mechanism to control LTC Timing
    - Addressed in FY14-15
  - LTC high load and high speed operation
    - Covered in FY12-13
  - LTC control during change of speed and load
    - Addressed in FY16 and beyond

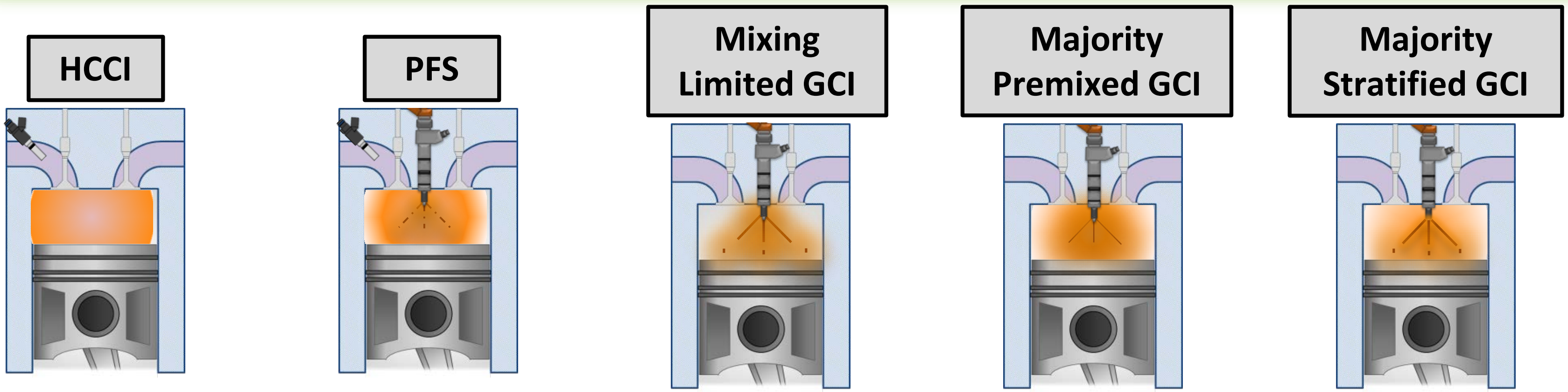
Partners

- GM R&D
  - Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- University of California – Berkeley
  - E10 LTHR/auto-ignition correlation
- ORNL
  - Different combustion approaches based upon reactivity of fuel
  - ORNL to use higher reactivity gasolines

OBJECTIVES/RELEVANCE: MULTI-CYLINDER, HIGH EFFICIENCY GASOLINE COMPRESSION IGNITION

Long-Term Objective

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system



Graphics courtesy ORNL (Curran & Dempsey)

OBJECTIVES/RELEVANCE: MULTI-CYLINDER, HIGH EFFICIENCY GASOLINE COMPRESSION IGNITION

Long-Term Objective

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

Current Specific Objectives:

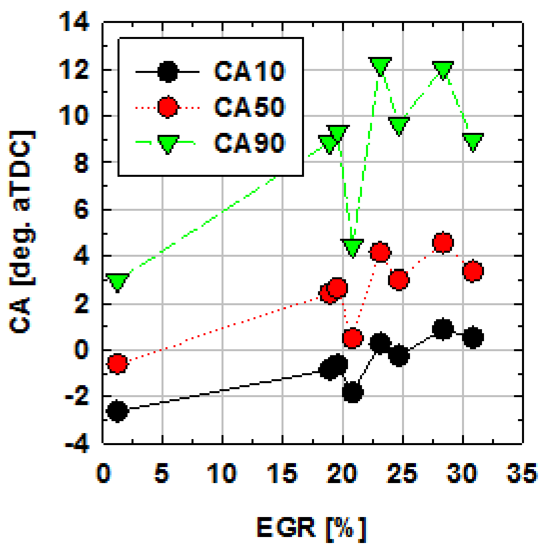
1. **Evaluate effect of Low Pressure EGR upon auto-ignition and engine performance characteristics**
2. **Quantitatively study effect of injection strategy upon auto-ignition to develop approach for transient operation and reduced fuel sensitivity**
3. **Perform factorial experiments to quantify the effect of important input parameters upon engine performance, noise and emissions**

MILESTONES

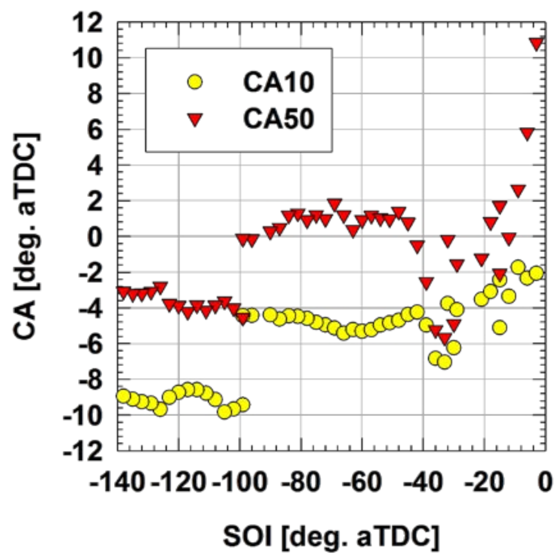
Milestone	Target Date
Determine nozzle inclusion angle effects upon high load combustion noise and PM/NO_x (120 deg works well @ high load)	Jun 2015 (Completed)
Determine injection strategy requirements to enable transient operation (Time-based injections work well)	Sept 2015 (Completed)
Install Low Pressure EGR Loop	Dec 2015 (Completed)
Quantify boost sensitivity of E10 (Less than E0 but only marginally less sensitive)	Mar 2016 (Completed)
Develop strategy for GCI operation for entire speed/load range on E10 (Integrate LP-EGR, Boost and injection strategy)	June 2016 (Ongoing)
Characterize PM from GCI using E10	Sept 2016 (Ongoing)

APPROACH/STRATEGY: USE INJECTION STRATEGY, LP-EGR, SIMULATION & MULTI-CYL OPERATION TO UNDERSTAND IGNITION AND OPERATING BOUNDARIES

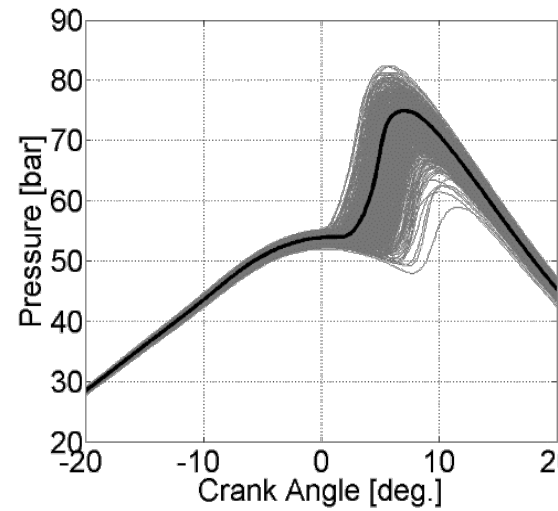
- Run experiments and utilize validated CFD modeling to understand factors involved in GCI auto-ignition
  - Injection strategy (# of injections, timing, dwell, fuel allocation, injection pressure)
  - LP-EGR at high loads– maintain high ignition reliability while lowering combustion noise and NO_x
  - Use validated modeling to assist in choosing optimum conditions
    - Feedback data to Global Sensitivity Study/Uncertainty Quantification on HPC (Som & Kodavasal)



<u>EGR sweep</u>: combustion phasing delay with LP-EGR



<u>Minimum fueling</u> strategy altered to more accurately control variables



CFD Simulations showing spread of pressure traces with perturbed inputs provided by experiment (IVC conditions, fueling rate etc.),

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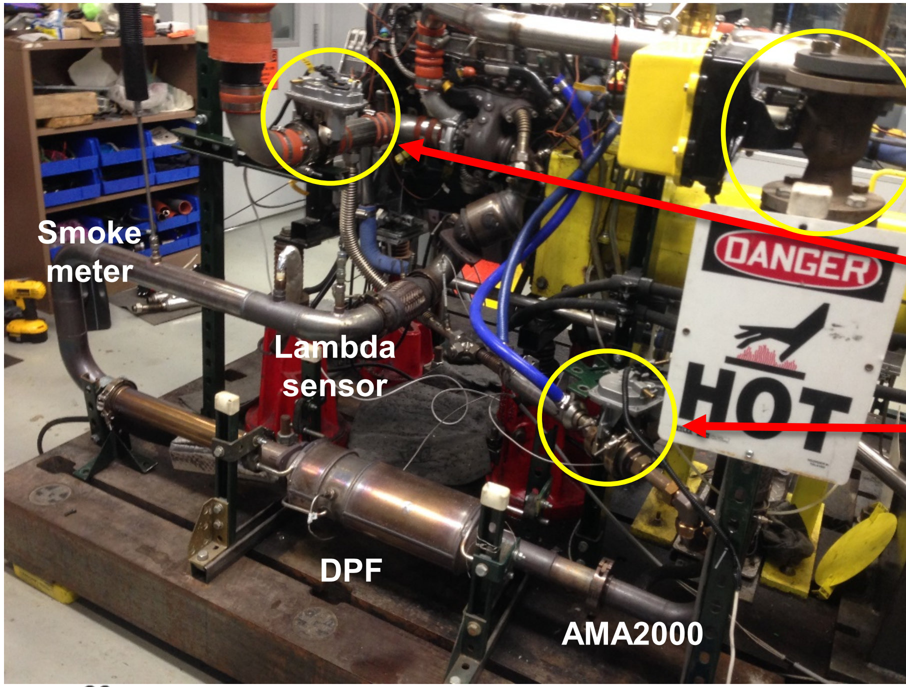
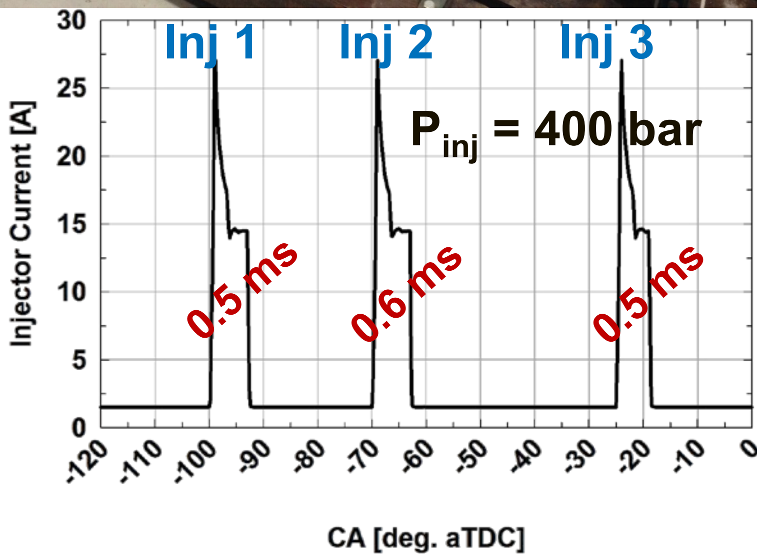
TECHNICAL ACCOMPLISHMENTS & PROGRESS

LP EGR SETUP & TESTING CONDITION





LP EGR Adjustment by means	
Exhaust Valve	**Throttle valve on overall exhaust discharge**
Inlet Valve	Throttle on fresh intake air upstream of turbo, to drive LP-EGR
LP EGR Valve	Throttle valve between post DPF exhaust and turbocharger intake

Test condition:

- EGR% sweep at constant load **(BMEP ~ 3 bar at 2000 RPM)**
- EGR% adjusted by separate valves (*most effective* **exhaust valve**)
- Triple injection (SOI of each: 100-70-25 deg. bTDC)
- Supercharger (ON) for P intake = 0.6 bar
  - Allows for precise control of intake pressure!

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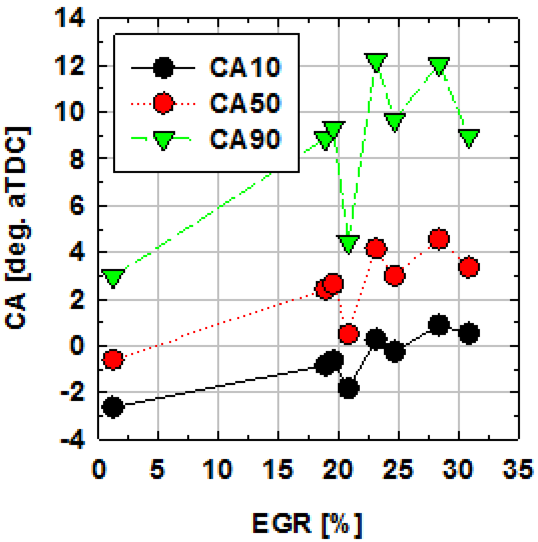
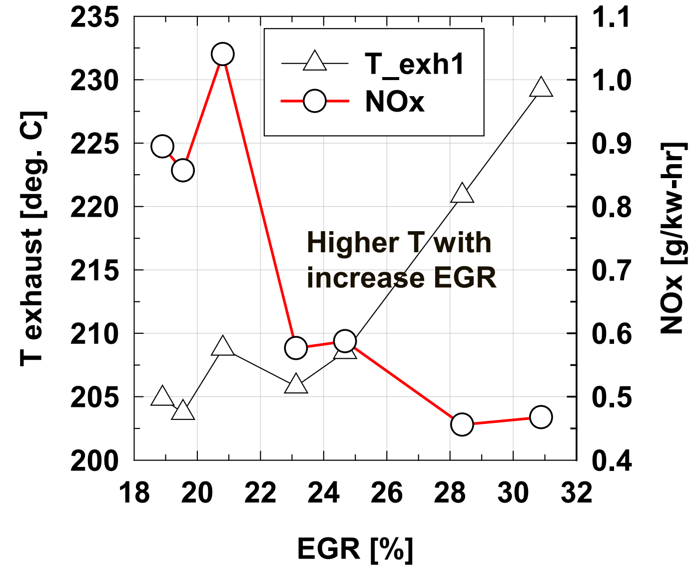
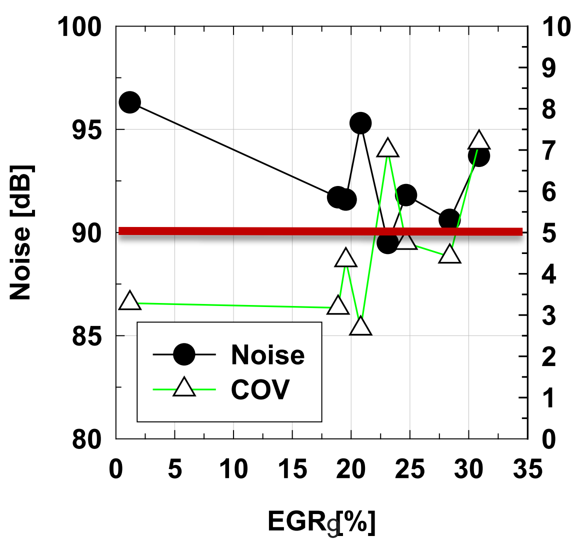
LP-EGR: EFFECTIVE AT MANAGING COMBUSTION PHASING, NOISE AND EMISSIONS, EXHAUST T



- Ignition and combustion phasing are retarded at higher EGR
- Can retard more with later 3rd injection
- Increased P_inj can mitigate PM increase



GM 1.9 L	17.8:1 (CR)
Engine speed	2000 rpm/3 bar BMEP
Injection pressure	400 bar
Injector-Bosch	7 hole 120 deg umbrella angle
Fuel	E10



- EGR helped lowering noise level (USCAR upper limit of 90 dBA in red)
- NO_x also reduced significantly with additional EGR
- Additional work needed to reduce COV increase

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LP-EGR IMPROVES PERFORMANCE AT HIGHER LOADS AS WELL

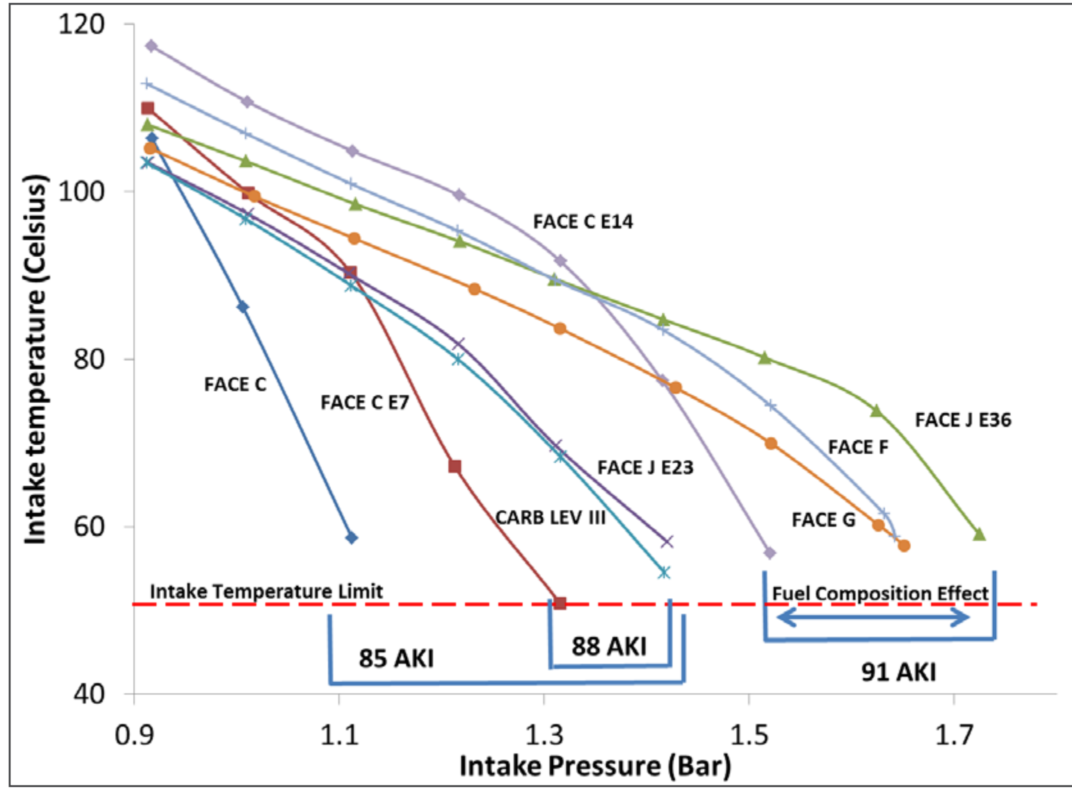
EGR	Intake T	T_exh	BMEP	BSFC	Noise	NO_X	HC	CO	FSN
[%]	[deg. C]	[deg C]	[bar]	[g/kw-hr]	[dB]	[g/kW-hr]	[g/kW-hr]	[g/kW-hr]	[a.u.]
29.41	53.64	309.5	4.32	346.13	90.13	0.45	0.91	2.10	0.030
29.84	45.56	316.9	4.91	312.04	93.90	0.42	1.16	3.20	0.017
29.43	47.11	327.5	5.16	317.10	91.58	0.33	0.57	1.34	0.020
30.50	47.58	419.9	8.27	280.25	93.88	0.04	0.37	1.27	0.027
30.48	47.91	412.2	8.33	278.78	91.01	0.05	0.37	1.44	0.024

GM 1.9 L	17.8:1 (CR)
Engine speed	2000 rpm
Injection pressure	400 bar
Injector-Bosch	7 hole 120 deg cone angle
Fuel	E10

- Emissions (NO_x, HC, CO) and FSN are reduced significantly with LP- EGR
- Exhaust temperature remains high with EGR
  - Improved aftertreatment expected with higher exhaust T
- Supercharger needed to maintain boost stability
  - Lower BSFC than intended
  - LP-EGR modifications to allow use of turbo only

COLLABORATION - UCB WORK SHOWS SIGNIFICANT LTHR DEPENDENCE FOR GCI

- Study at UCB (Vuillemier) shows that LTHR has significant effect on gasoline HCCI ignition
- His conclusions indicate:
  - A fuel's Octane Index is a good indicator of its GCI Low-Load Performance
  - LTHR Onset Pressure in an HCCI engine correlates very well with GCI Low-Load Performance.
  - ***<u>Increased intake pressure increases low-temperature heat release, enabling lower loads in a GCI engine</u>***

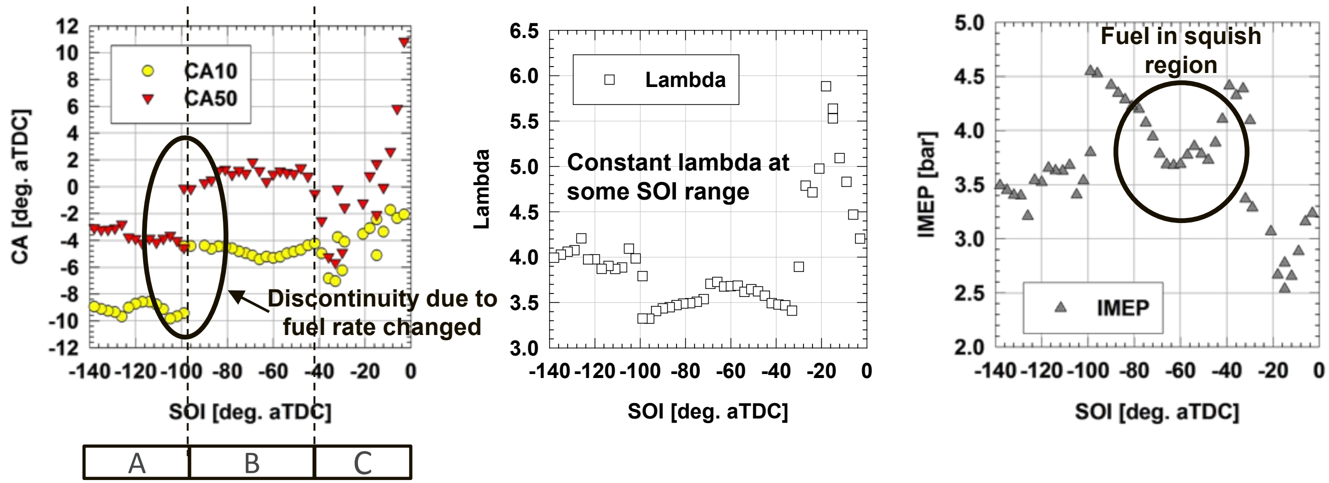


Courtesy of David Vuilleumier (August 2015 AEC meeting)

INJECTION STRATEGY: E10 MINIMUM FUELING – SOI SWEEP

GM 1.9 L	17.8:1 (CR)
Engine speed	1000 rpm
Injection pressure	400 bar
Injector-Bosch	7 hole 120 deg. cone angle
Fuel	E10

- **Minimum Fueling** approach: least fuel requirement for stable combustion (COV_{IMEP} < 3%)
- Combustion mode (**HCCI vs. GCI**) characterized by **SOIs**

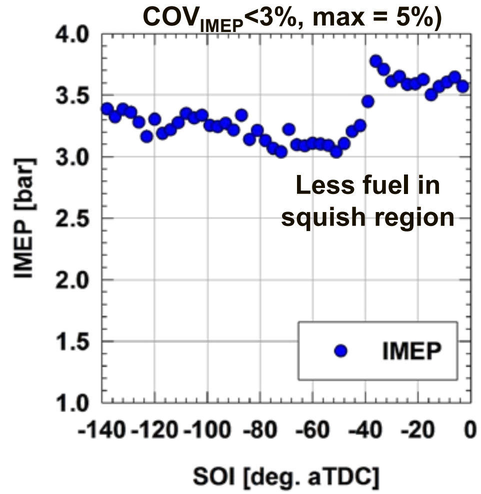


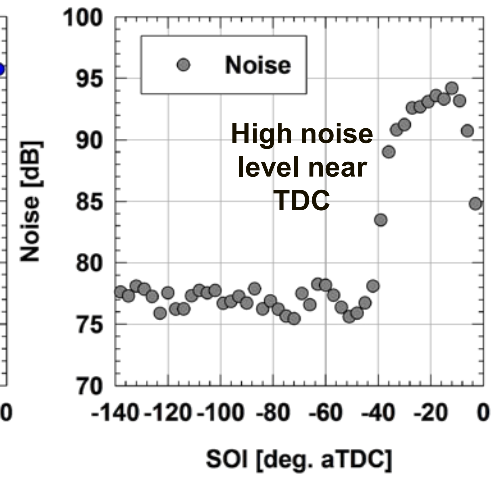
- **A-period** Location of ignition (CA10), and combustion phasing (CA50) seems stay constant
- **B-period** More fuel (smaller lambda) is needed to have stable combustion, but CA10/CA50 also seems constant
- **C-period** IMEP shows a drop near -60 deg. aTDC due to possible fuel entering squish region

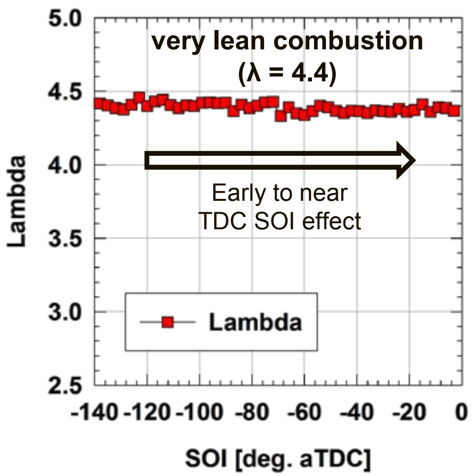
- Both **SOI and Lambda** show to have effect on CA10/CA50, but lambda is more effective
- There seems to be a condition with **constant lambda** to fix CA10/CA50

E10 CONSTANT LAMBDA – SOI SWEEP

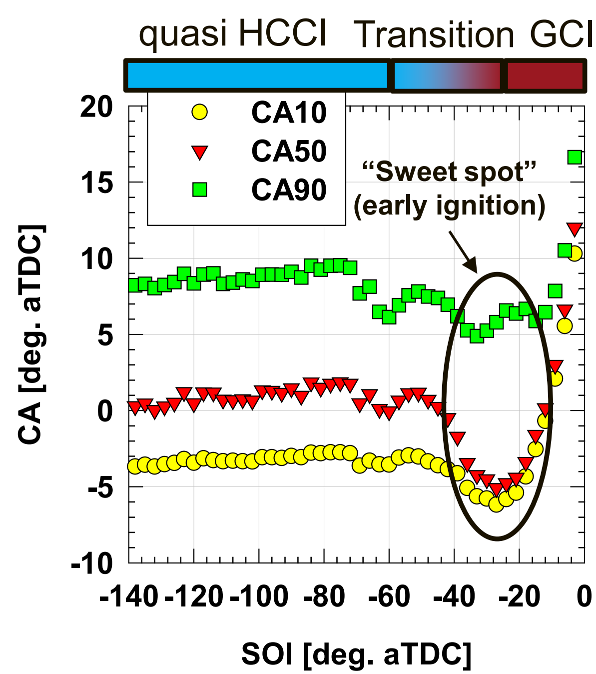
- *Minimum fuel* provides fuel requirement (least fuel) for combustion stability, but does not give same mixture to study SOI effect explicitly on ignition and combustion → **constant lambda approach**
- Fuel rate was adjusted to keep same lambda through all SOIs
- λ calculated from **emission bench**



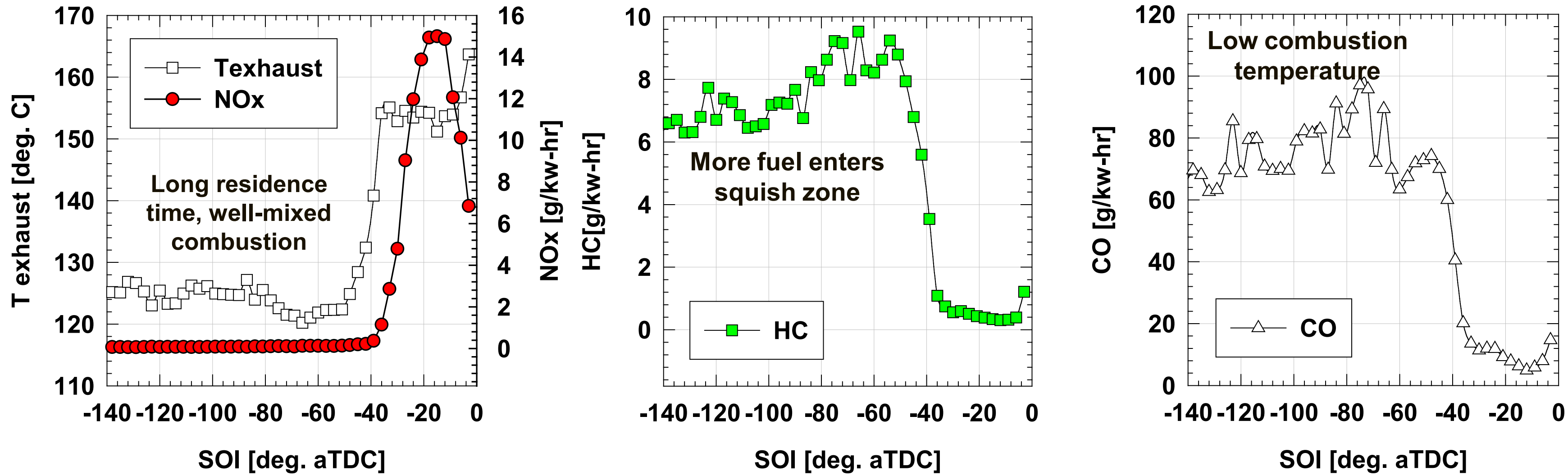




- Almost similar **ignition location** in "quasi HCCI" (also similar CA50/CA90)
- Existing region where **earliest ignition** occurs (near -30 deg. aTDC) – reduction in fuel in squish region
- Near TDC, short **residence time** for ignition
- IMEP increases slightly near TDC (less fuel in squish)
- It was harder to control noise level with late injection



LOW SPEED/LOAD E10 CONSTANT LAMBDA – SOI SWEEP: EMISSION



GM 1.9 L	17.8:1 (CR)
Engine speed	1000 rpm
Injection pressure	400 bar
Injector-Bosch	7 hole 120 deg cone angle
Fuel	E10

Early injection:

- **Low level of NOx** in highly homogeneous mixture (quasi HCCI region)
- Incomplete combustion (**high HC**)
- Low combustion temperature → **high CO**
- Smoke number (FSN) was very low (<0.1) due to lean condition at all SOIs

Late injection (GCI mode):

- Insufficient time for air/fuel mixing
- **High NOx** due ~ high combustion temperature; richer zones for ignition
- **Less HC and CO** (aggressive reaction leads to more complete combustion)

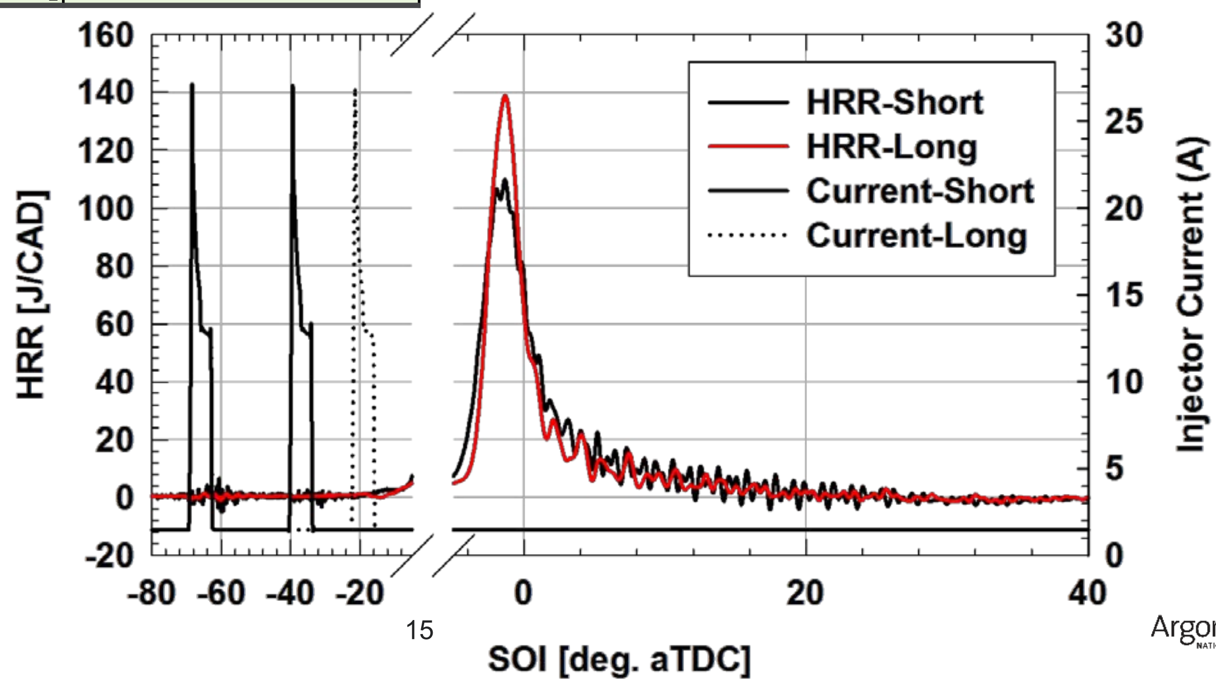
PARAMETRIC STUDY: HIGHER ENGINE SPEED CONDITION (2000 RPM)

Engine Speed	2000 rpm	
Level	Low	High
Constant Boost	0.45	
Injection pressure [bar]	400	600
SOI [deg. BTDC]	70/20	70/40
Lambda	2.7	3.7
Constant Lambda	3.1	
Injection pressure [bar]	400	600
SOI [deg. BTDC]	70/20	70/40
Boost [bar]	0.35	0.55

Considered parameters

P	Injection Pressure
S	Start of injection
L	Lambda
B	Boost

Sample AHRR of long vs short dwell: P_{inj}=600 bar, P_{Intk}=0.55 bar, λ = 3.1



Double injection:

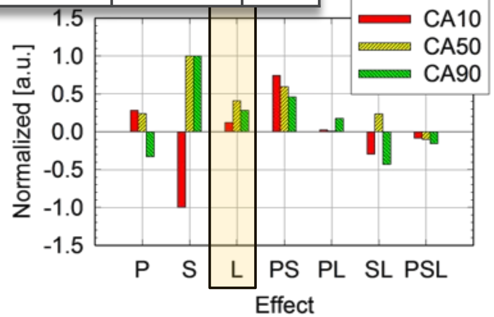
- Same duration for pilot & main
- Fixed pilot
- Helpful for meeting COV, noise levels

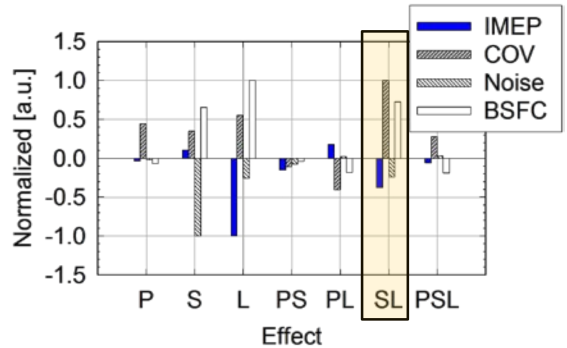
FACTORIAL STUDY - CONSTANT BOOST TESTS SHOW INFLUENCE OF COMBUSTION MODE ON EMISSIONS, LAMBDA ON COMBUSTION PHASING

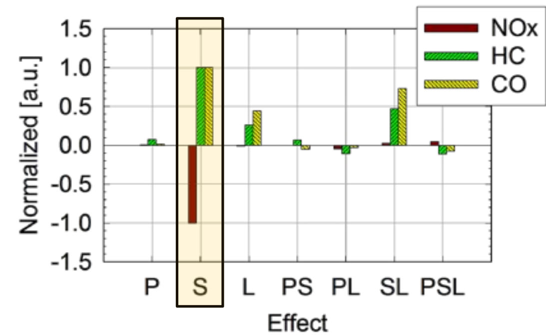
P	Injection Pressure
S	Start of injection
L	Lambda
B	Boost

B [bar]	0.2	
P [bar]	400	600
S [deg. bTDC]	15	141
L	3.6	4.5

1000 RPM

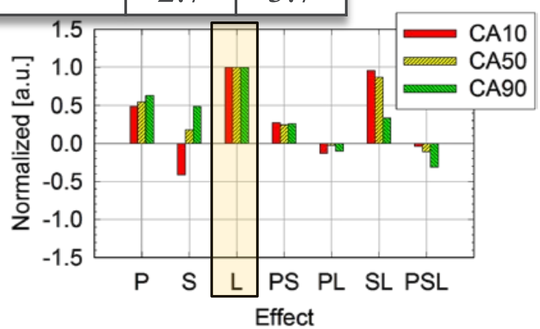






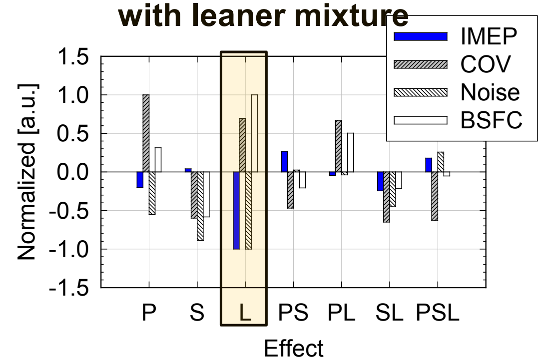
B [bar]	0.45	
P [bar]	400	600
S [deg. bTDC]	70/20	70/40
L	2.7	3.7

2000 RPM

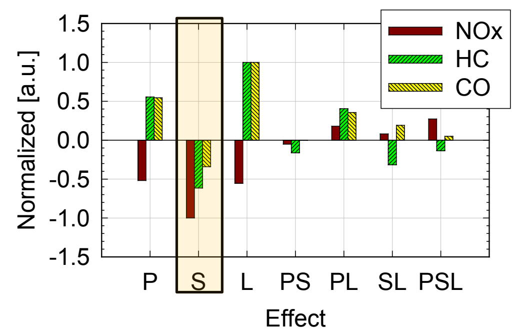


λ has strong impact on ignition

Lower performance with leaner mixture



Lower emissions with shorter dwell

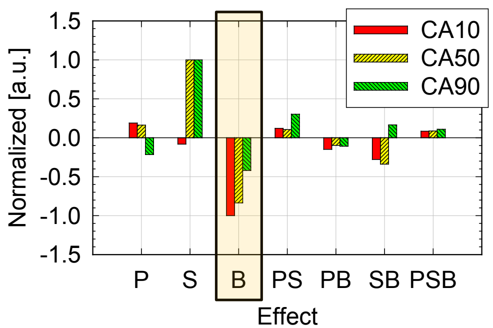


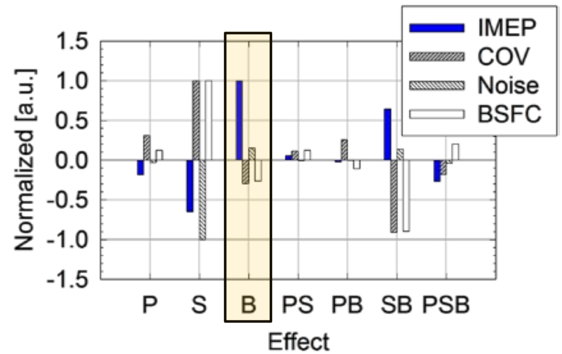
FACTORIAL STUDY - CONSTANT LAMBDA TESTS SHOWS SIGNIFICANT BOOST EFFECT ON COMBUSTION PHASING, NOISE AND EMISSIONS

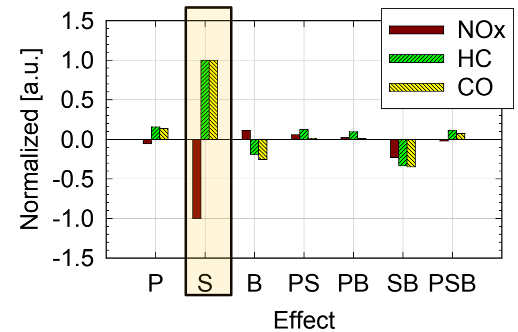
P	Injection Pressure
S	Start of injection
L	Lambda
B	Boost

L	4.2	
P [bar]	400	600
S [deg. bTDC]	15	141
B [bar]	0.15	0.3

1000 RPM

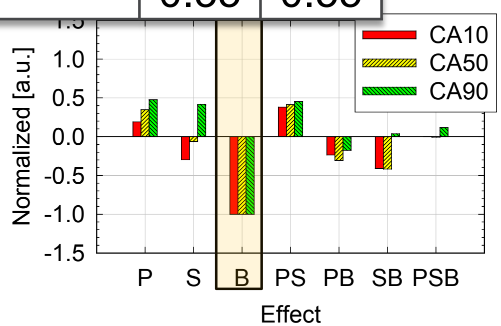






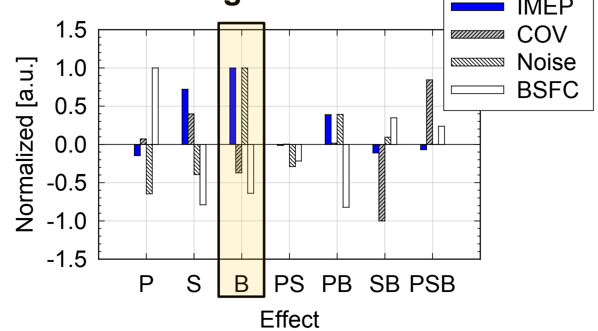
L	3.1	
P [bar]	400	600
S [deg. bTDC]	70/20	70/40
B [bar]	0.35	0.55

2000 RPM

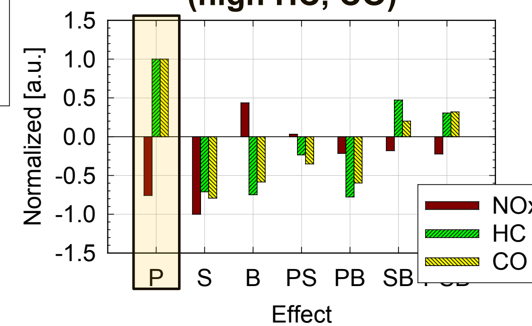


Advanced ignition at higher boost

Reduced COV, BSFC, Increased Noise at higher boost



Overmixed at high P_inj (high HC, CO)



RESPONSES TO FY15 REVIEWER COMMENTS

Reviewer Comment	**Response**
Efficiency/noise tradeoff?	Specifically addressed this year in trying to keep noise below 90 dBA
How to address low exhaust temperatures at low load?	LP-EGR, along with late injection timing, appear to have the leverage to increase exhaust temperature at low load
Perhaps too much attention paid to imaging, not enough to injection strategy for LD installation?	Less focus on endoscopic imaging, more focus on injection strategy and implications for transient operation; understanding different modes of operation for different speeds/loads
Additional PM characterization?	Collaboration with HeeJe Seong (TEM sampling) and additional SMPS/EEPS measurements. FSN mostly for operational interest

COLLABORATIONS

Engine maps, piston crowns and other hardware, cylinder head modifications, technical support

- **E10 LTHR influence upon auto-ignition**
- **Fuel influence on LTHR**

- **Collaboration with Scott Curran**
- **High reactivity fuels @ ORNL**
- **Low reactivity fuels @ ANL**
- **Comparison of mixture stratification levels**

(IQT Fuel characterization)

- In addition, this project is involved in the AEC Working Group
  - Cummins, CAT, DDC, Mack, John Deere, GE, International, Ford, GM, Chrysler, ExxonMobil, ConocoPhillips, Shell Chevron, BP, ANL, SNL, LLNL, ORNL, NREL
  - Co-Optima project is also related to this work

REMAINING BARRIERS AND CHALLENGES

- Reliable and repeatable ignition and combustion phasing
  - Characterize injection strategy as optimal for transient behavior
  - Characterize injection strategy to minimize slight fuel property variations
    - Octane number in particular, along with EtOH content
- Improve air handling to make LP-EGR more effect\ive
  - Better characterize injection/boost/EGR interactions
- Examine CR as influence for Combustion Noise/BSFC tradeoff
- Study influence of these parameters upon PM to insure future EPA compliance

PROJECT FUTURE WORK

- ❑ Continue to explore/understand effect of injection strategy upon GCI operation
  - ➢ E10 is sensitive to both boost and EGR
- ❑ Explore more conditions with LP-EGR
  - ➢ Provide more boost at low speeds/loads with EGR
- ❑ Examine influence of CR upon combustion noise
  - ➢ Alter IVC relative to exhaust cam
  - ➢ Use lower CR piston crowns (we have 16, 15 and 14:1)
- ❑ Continue to develop strategy for transient operation with injection, boost and EGR
- ❑ Continue to track and account for USCAR guidelines combustion noise
  - ➢ Target <90 dB for high load, <85 dB for low load
- ❑ Continue to characterize GCI particulate emissions
  - ➢ TEM sampling and analysis

SUMMARY

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

1. LP-EGR has a significant effect upon combustion noise, combustion phasing, exhaust temperature and engine-out emissions.
2. Injection strategy is also influential to engine operating outputs
   - DoE analysis quantified effects of input variables
   - Boost and EGR were also found to have large influence
3. PM output is very low for GCI; almost all conditions below 0.1 FSN.
   - Detailed PM study is forthcoming; collaboration with HeeJe Seong

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

TECHNICAL BACK UP SLIDES

ENGINE SPECIFICATIONS AND TESTED FUELS PROPERTIES E10 WAS USED FOR IDLE AND LOW LOAD EXPLORATION

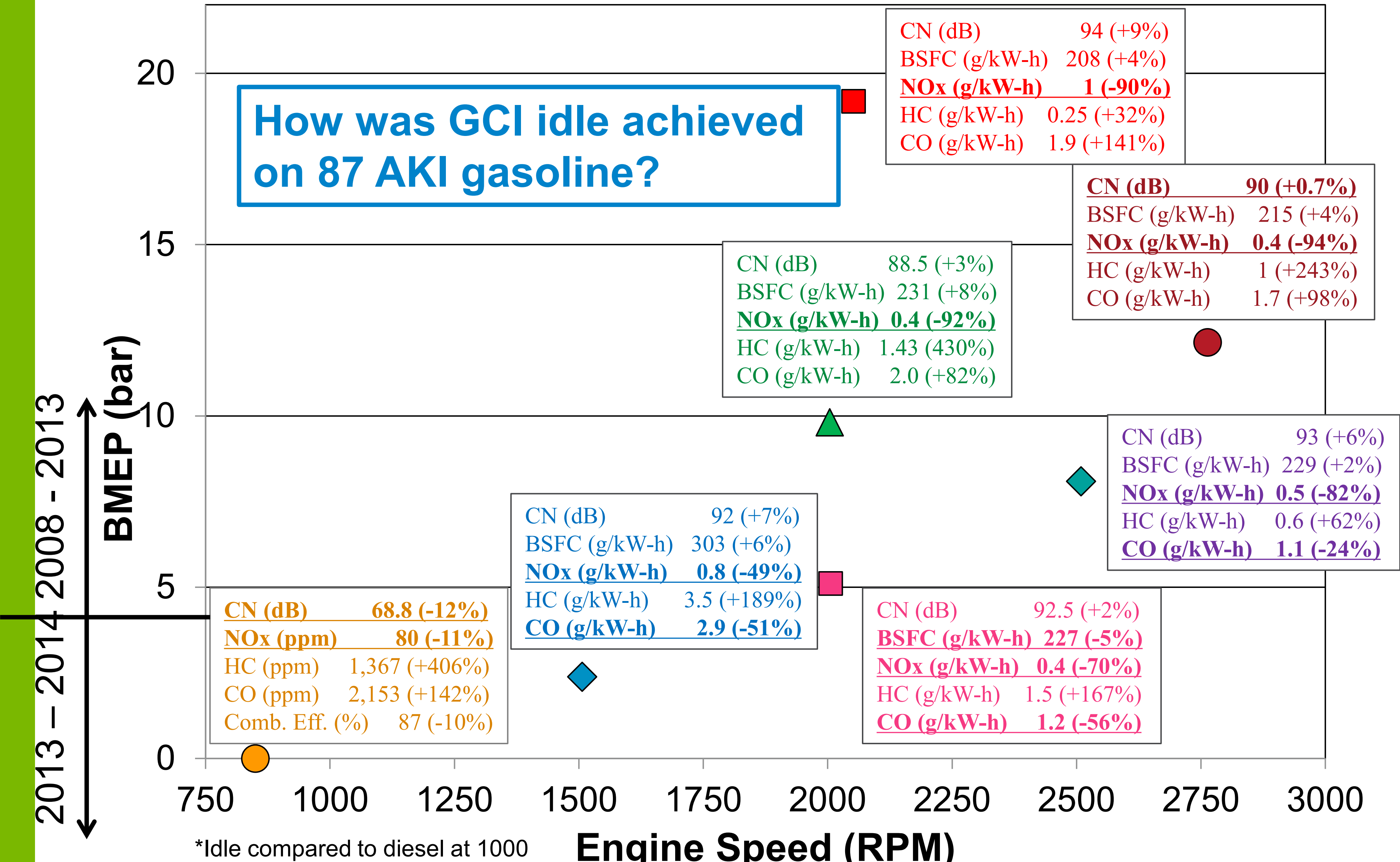
Engine Specifications

Compression ratio	17.8:1
Bore (mm)	82
Stroke (mm)	90.4
Connecting rod length (mm)	145.4
Number of valves	4
EGR System	High Pressure EGR Mixing far upstream for homogeneity
Injector	7 holes, 0.141-mm diameter
Umbrella Angle	148° and 120°
Injection Rail Pressure	500 bar and 250 bar
Boosting	Variable Geometry Turbocharger (VGT) And/or Eaton Supecharger

Properties of the Tested Fuel

Property	E10 gasoline
AKI Rating	87.2
RON	90.7
MON	83.7
Sensitivity	7
Specific gravity	.7342
Lower heating value (MJ/kg)	42.0
Initial boiling point (°C)	103.5
T10 (°C)	132.3
T90 (°C)	320.7

PROGRESS OF GCI LOAD RANGE USING 87 AKI GASOLINE

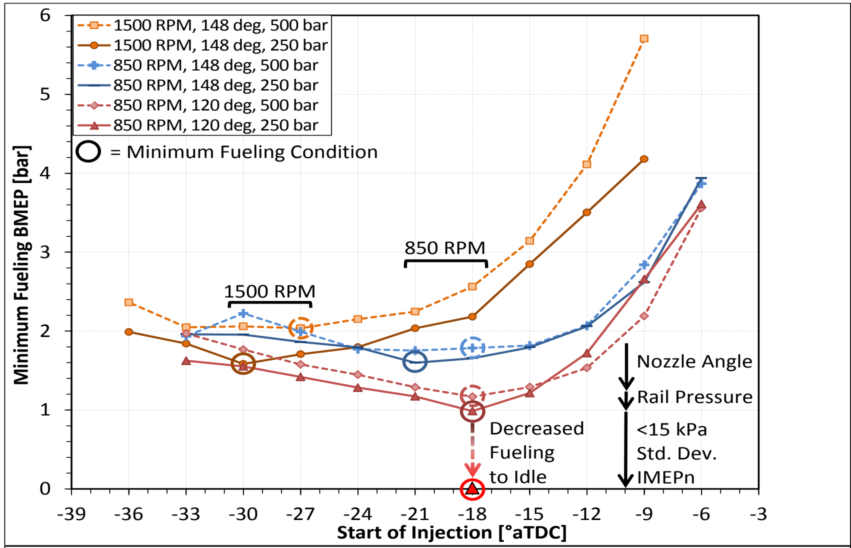


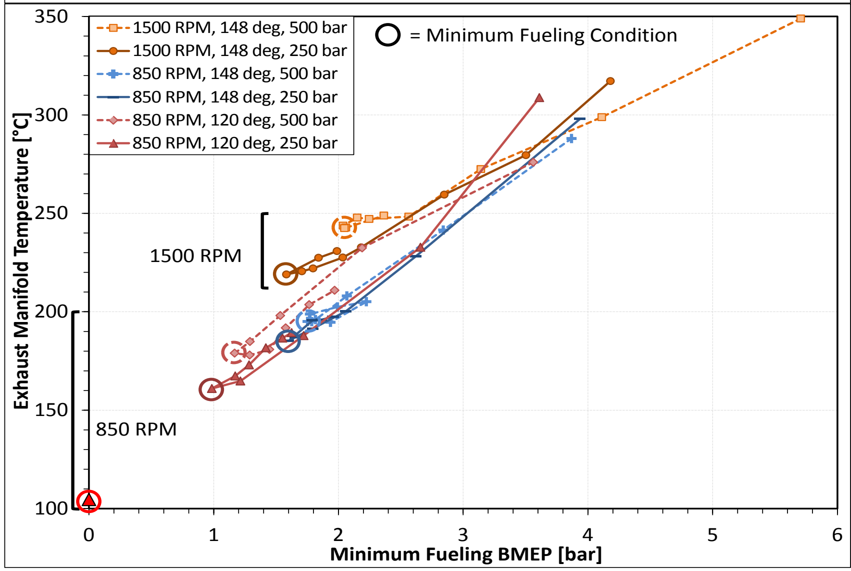
*Idle compared to diesel at 1000

EXPANSION OF LOWER LOAD LIMIT WITH 87 AKI GASOLINE

Methodology

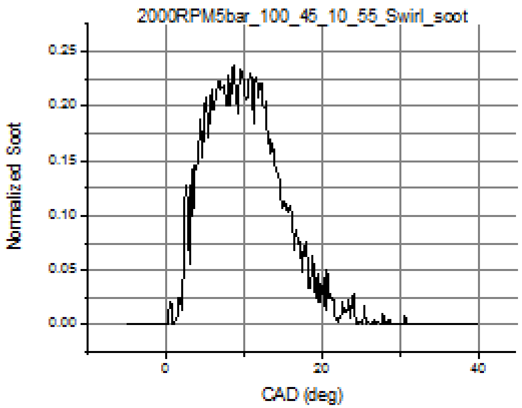
- Minimum fueling SOI sweeps
  - 3% CoV of IMEP limit for each cylinder individually
- Single injection per cycle
- 850 RPM engine speed (previous studies also done at 1500 RPM)
- 250 or 500 bar injection pressure
- 148° and 120° injector nozzle
- Combustion noise target <90 dB
- Maximized boost (1.05 bar)
- 45 °C intake air temperature
  - No external intake heating
- No EGR

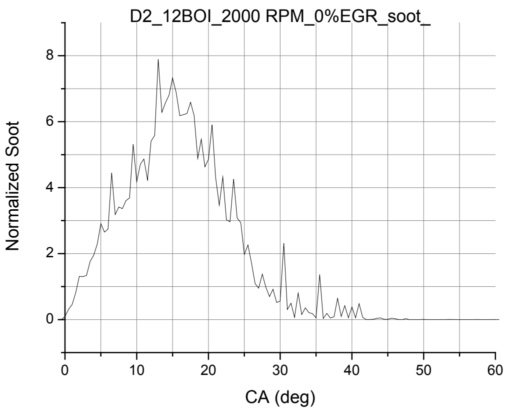




Based on SAE 2015-01-0832

SOOT RADIATION DIFFERENCES BETWEEN GASOLINE AND DIESEL





- 2-color optical technique is very effective at measuring soot production
- Graph in lower right (GCI) is with the same scale as graph in upper right (Diesel)
- Optical diagnostics can be effective at identifying boundary conditions for GCI