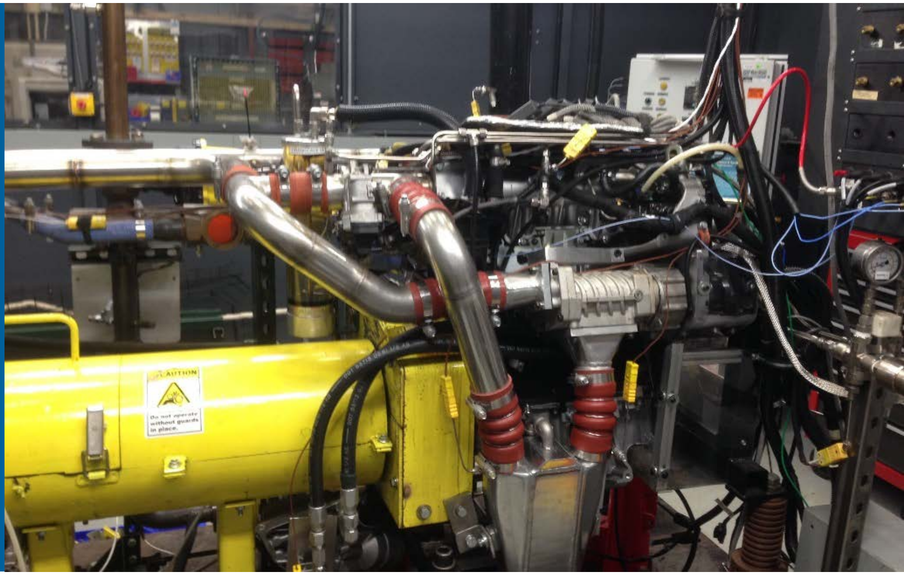
Project ID# ACS011

# ADVANCES IN HIGH-EFFICIENCY GASOLINE COMPRESSION IGNITION




**STEPHEN CIATTI, CHRISTOPHER KOLODZIEJ, VASUDHA PATRI**


2018 DOE Vehicle Technologies Office Annual Merit Review
Advanced Combustion Systems
8:30 AM, Wednesday, June 20, 2018

DOE Vehicle Technologies Office Management:
Gurpreet Singh & Michael Weismiller

# OVERVIEW

## Timeline

- Started Oct 2016
- End date Sept 2019
  - Lab Call reset Sept 2018
- 50% Completed

## Barriers

- From 2018 ACEC TT Roadmap
  - LTC control methods and technologies
  - Effects of fuel injection
    - Number and timing of injections
    - Fuel quantity splits
  - Part-load HC and CO reduction

## Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY17 $410k
  - FY18 $423k

## Partners

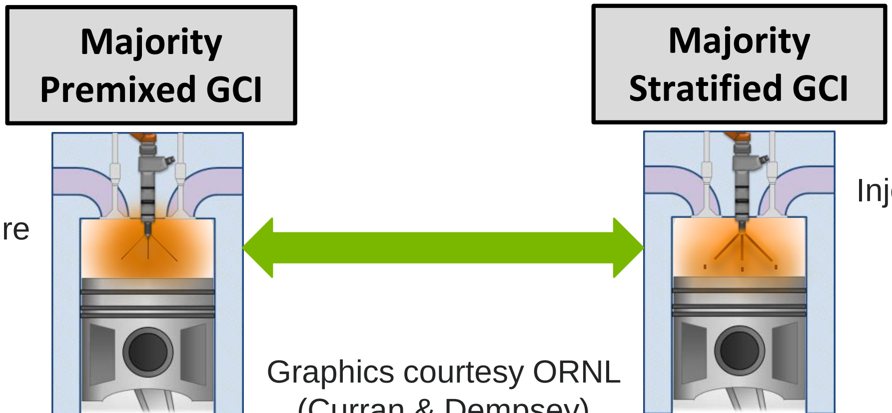
- GM R&D
  - Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- Eaton

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

## Long-Term Objective

**Support DOE LTC research through a better understanding of the physical and chemical characteristics of Gasoline Compression Ignition (GCI) combustion in a multi-cylinder engine for high efficiency and low emissions**

**Benefits:**
Lower NOx/PM
Lower Combustion Temperature




Graphics courtesy ORNL (Curran & Dempsey)

**Benefits:**
Injection-Based Combustion Control
Lower HC/CO emissions

## Current Specific Objectives:

1. **Improve knowledge of cylinder conditions necessary for stable part-load GCI combustion with low combustion noise, emissions, and fuel consumption using:**
   a) **Injection strategy (mixture conditions)**
   b) **EGR (NOx control)**
   c) **Intake temperature (reactivity)**
   d) **Boost level (combustion stability)**
2. **Identify the future pathway for high efficiency, low emissions full-time GCI research**

# APPROACH (EVOLUTION 2017-2018)

- Project approach as of Mar-Jun, 2017:
  - Final GCI baselining and endoscopic imaging (Sept, 2017 milestone) on Euro IV 17.5:1 CR GM LD diesel multi-cylinder engine
  - Receive and install Euro VI 15:1 CR Volvo LD diesel multi-cylinder engine
  - Break-in and baseline Euro VI Volvo engine on diesel fuel, then GCI
  - Show potential upper load expansion of LTC operation at 15:1 versus 17.5:1 CR, improved BTE, emissions, combustion noise, etc. (Mar, 2018 milestone)
- Aug, 2017:
  - Mazda announces 2019 release of SKYACTIVE-X (Multi-mode SPCCI*/SI combustion)
- Nov-Dec, 2017:
  - Initial ACEC guidance on updated LD ACEC roadmap
  - Only Multi-mode LD LTC research (low-mid load LTC, mid-high load SI combustion)
  - Engine platform similar to light-duty downsized boosted gasoline engine
- Jan-Feb, 2018:
  - ANL discussions regarding continuation of full-time GCI vs. multi-mode (LTC/SI)
- Mar-Apr, 2018:
  - Transfer project PI responsibilities from S. Ciatti to C. Kolodziej
  - Feedback that MD/HD OEMs are open to full-time GCI
  - Decision to transition full-time GCI work to Argonne's HD Caterpillar single-cyl. engine
  - Caterpillar confirms interest and support for project
  - HD GCI approach:  LTC at low-mid loads where possible and gasoline diffusion combustion at mid-high loads





* Spark Plug Controlled Compression Ignition

# APPROACH

- Final GCI testing on Euro IV 17.5:1 CR GM LD diesel multi-cylinder engine
  - Potentially applicable to multi-mode LTC/SI gasoline engine with high geometric CR
  - Reports that Mazda SKYACTIVE-X engine may have 15-16:1 geometric CR*
- Low-mid load LTC test point (per ACEC TT Guidance+)
  - 2000 RPM, 6 bar IMEP
- Focus on indicated parameters for combustion strategy development
- Develop method to quickly characterize a given speed-load condition in GCI for a certain piston, injector, and fuel combination
  - Constant combustion noise (90 dB) sweeps of key combustion control parameters
- Comparison of injection strategies (number, timings, splits, pressure)
  - Constant 90 dB combustion noise (CN) target
  - <0.1 FSN
  - Find lowest ISFC, ISHC, and ISCO emissions
- Minimum EGR to meet NOx target
- Minimum boost pressure required for combustion stability

*Automotive Engineering, Oct., 2017
+ ACEC Roadmap, March, 2018

# MILESTONES

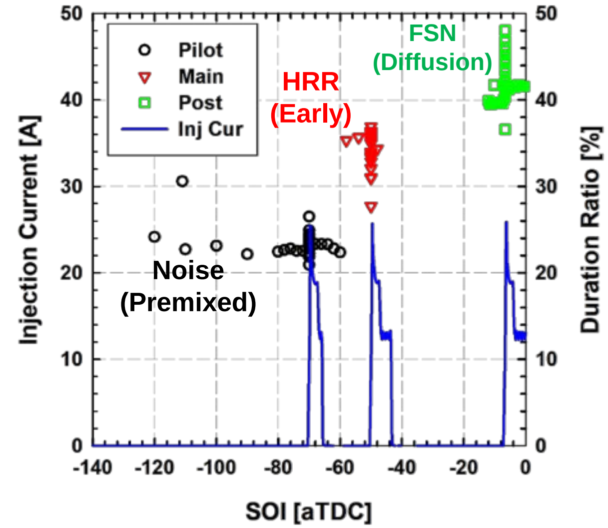
| Milestone | Target Date |
| --- | --- |
| Endoscope imaging of GCI combustion luminosity and chemiluminescence for multiple injection to study soot and temperature, and CH*/OH*, respectively | Sept 2017 (Incomplete) (Endoscope damaged) |
| Assess impact of CR 15:1 upon injection and operational approach on E10, focusing upon ignition delay, combustion phasing and combustion noise impacts compared to CR 17.5:1 for NVH and CA10/CA50 control | Mar 2018 (Complete) |

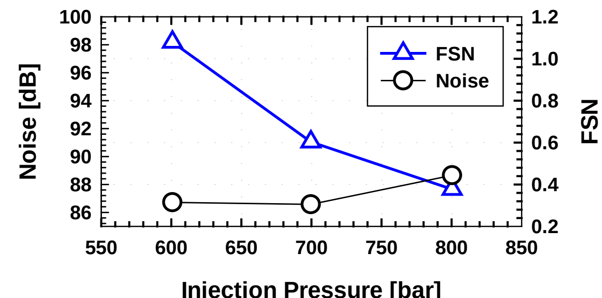
- Reduced intake pressure was used to achieve similar cylinder pressure at TDC as 15:1 CR engine
  - Reactivity was significantly reduced, requiring significantly increased intake temperature
- At 17:1 CR, performed sweeps of key GCI combustion control parameters at 2000 RPM, 6 bar IMEP and constant 90 dB combustion noise

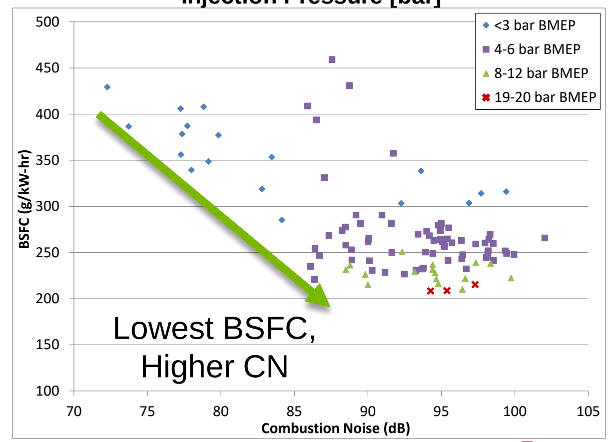
# TECHNICAL ACCOMPLISHMENTS & PROGRESS

# BUILDING ON PREVIOUS RESEARCH

- 2017 AMR work covered 7-16 bar IMEP:
  - Focused on 10 bar gIMEP (8 bar BMEP)
  - Triple injection strategy timings, splits
    - Two early, one late
  - Rail pressure reduced soot emissions
- 2018 AMR focus on part-load GCI (ACEC Guidance):
  - 2000 RPM, 6 bar IMEP
  - Constant 90 dB testing
    - Typically CN has been the more restrictive parameter for reaching highest engine efficiency
- Key combustion control parameters investigated:
  1. Injection #, timings, and splits for lowest ISHC, ISCO, and ISFC (no EGR yet) at constant 90 dB CN
     - Minimum boost required for combustion stability
     - Minimum injection pressure (400 bar) to maximize stratification
  2. Minimum EGR required for NOx target
  3. Effects of intake temperature (IVC temp) on reactivity



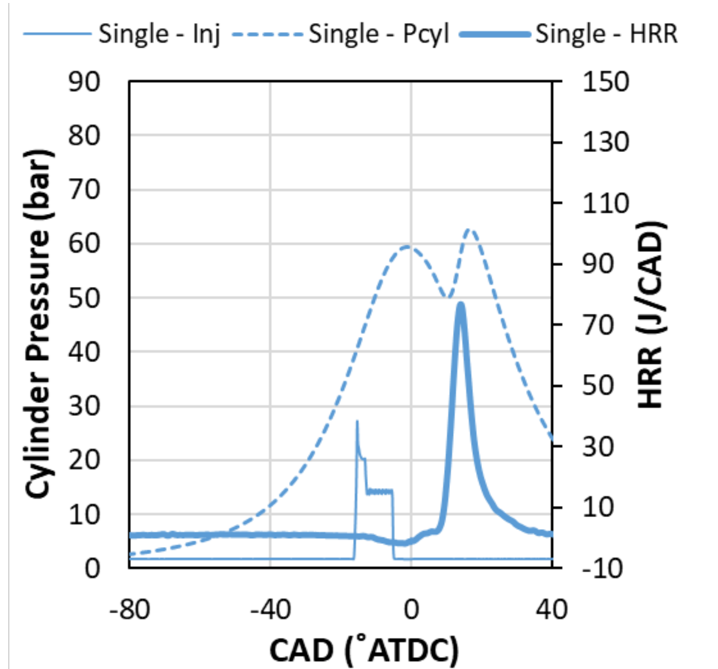



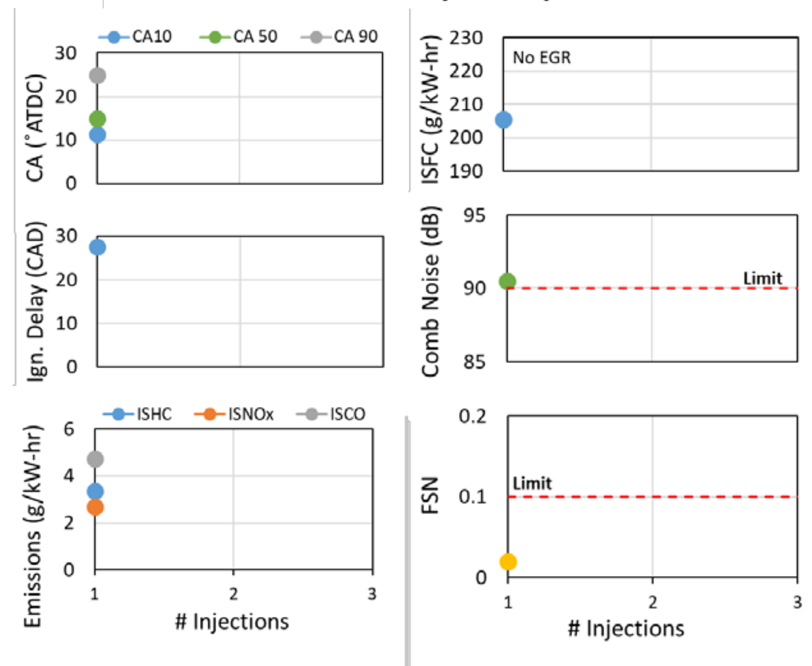



Ciatti & Cung, 2017 VTO AMR

# INJECTION QUANTITY – SINGLE

- Initial tests with no EGR to allow widest range of injection parameters to be tested
- All combustion limits could be met with a single injection at 1.44 bar boost
  - Including 3% CoV of IMEP

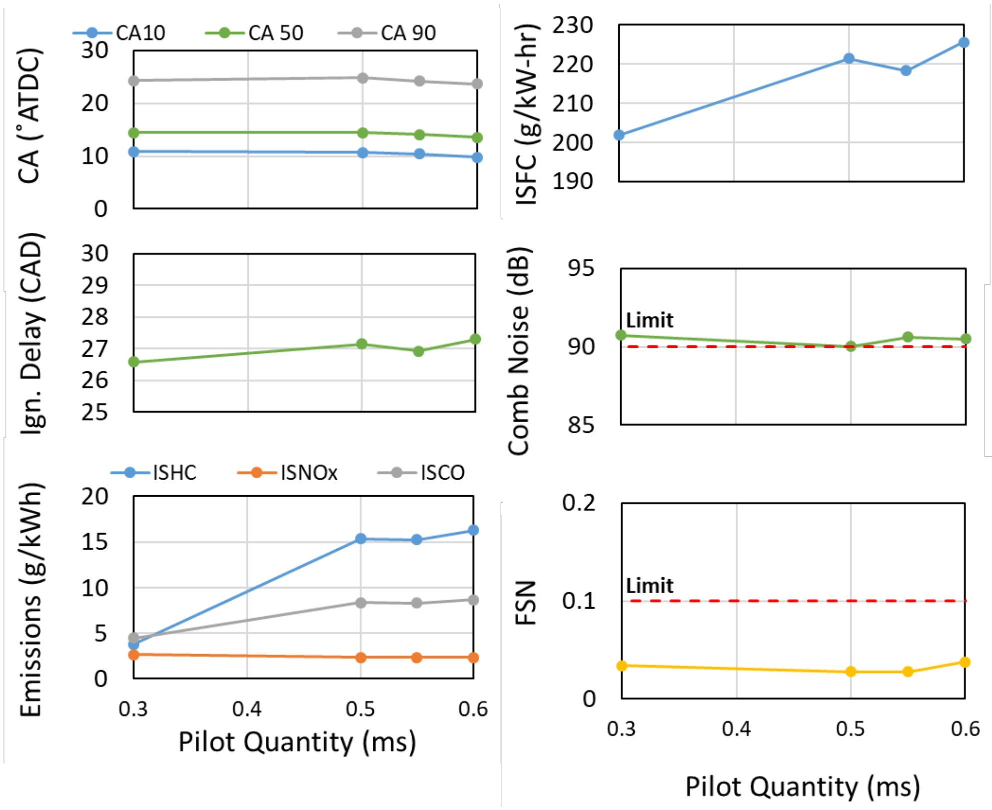



| Parameter | Value |
|---|---|
| Engine Speed [rpm] | 2000 |
| Engine Load [bar IMEP] | 6 |
| Fuel | 87 AKI, E10 |
| Injection Pressure [bar] | 400 |
| EGR [%] | 0 |
| Boost Pressure [bar(a)] | 1.44 |
| Intake Air Temp [°C] | 50 |

# PILOT QUANTITY SWEEP

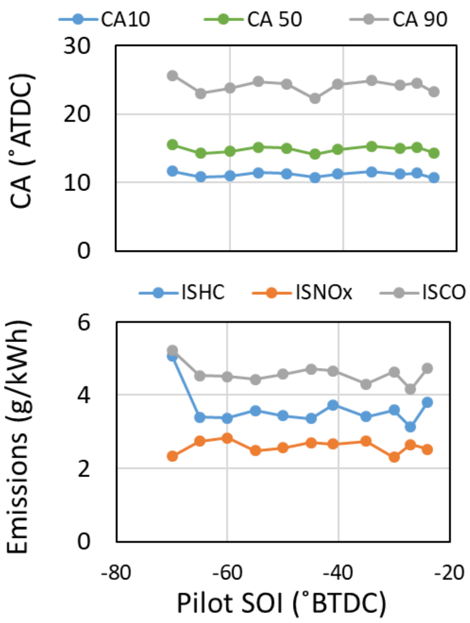
- Initial settings:
  - Pilot timing -70 °aTDC
  - Adjusted main injection timing for constant CN
- 2017 AMR mid-high load testing found that increased pilot injection increased CN and reduced FSN
- At constant CN and FSN under limit, reduced pilot decreased HC, CO, and ISFC significantly
- 0.3 ms min. restricted by injector
- Potential causes include:
  - Wall/piston wetting
  - Increased fuel into the piston crevice

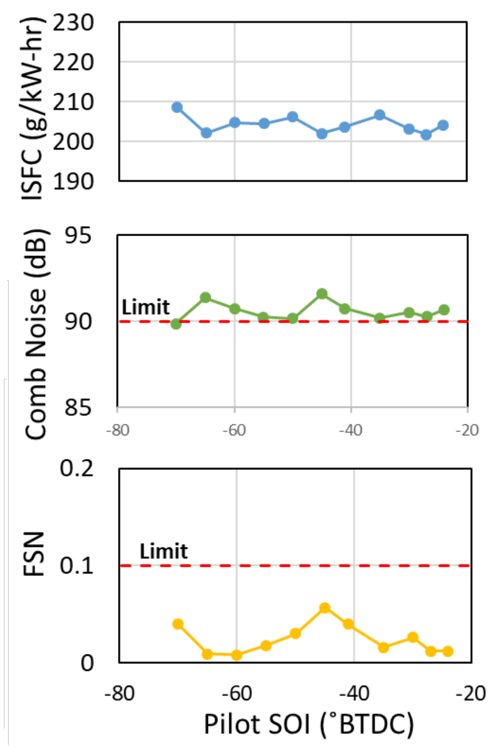



| | |
|---|---|
| **gIMEP/Speed** | **6 bar/2000 rpm** |
| **Tin/Pin(a)** | **50 °C/1.44 bar** |
| **Injection** | **Double** |

# PILOT SOI SWEEP

- Pilot SOI sweep performed at 0.3 ms
- Similar to 2017 AMR pilot SOI sweep at 2000 RPM, 10 bar IMEP, no significant effect
- Even the main injection timing and ignition delay were very similar among all pilot SOI timings
- However, earliest SOI (-70 °aTDC) showed increased HC and CO
- Therefore continuing pilot SOI chosen as -65 °aTDC with 0.3 ms

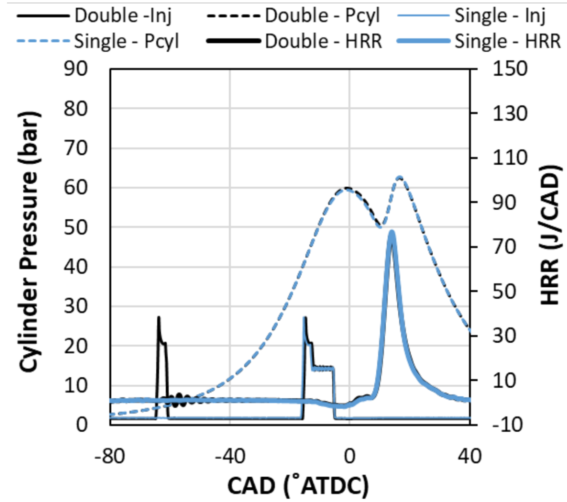


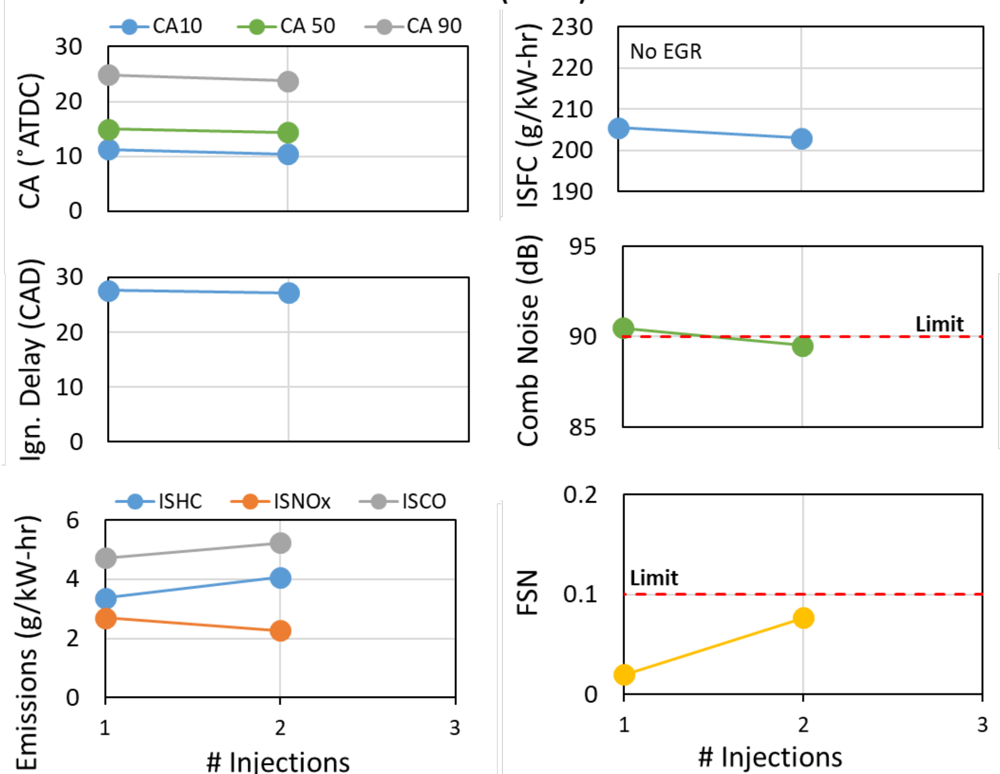




| gIMEP/Speed | 6 bar/2000 rpm |
|---|---|
| Tin/Pin(a) | 50 °C/1.44 bar |
| Injection | Double |

# SINGLE VS. DOUBLE INJECTION

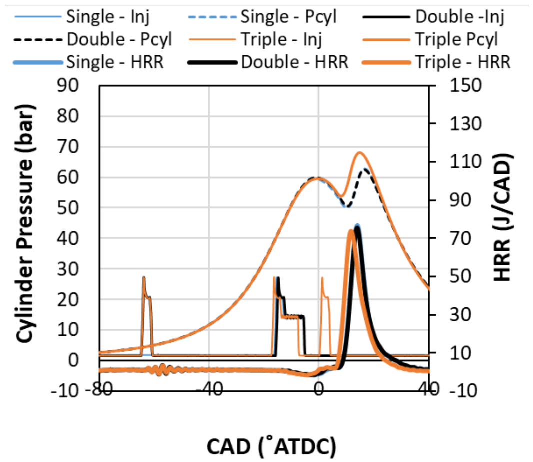
- Double injection with a small pilot injection had combustion metrics for the same combustion noise level
- Second injection still well before main heat release (27 CAD Ign Del)
- ISNOx slightly reduced with double injection
- Slight increase in HC and NO emissions despite a small advance of combustion phasing leads to a small reduction in ISFC



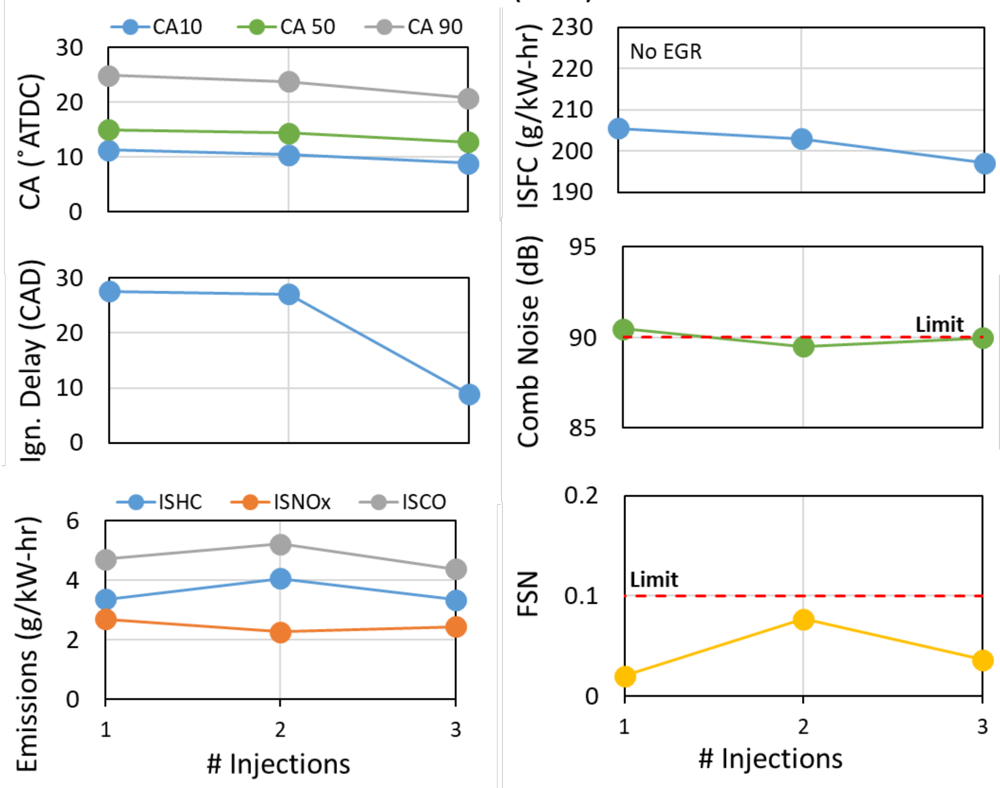




| | |
|---|---|
| **gIMEP/Speed** | **6 bar/2000 rpm** |
| **Tin/Pin(a)** | **50 °C/1.44 bar** |
| **Injection** | **Single/Double** |

# TRIPLE INJECTION (LATE DOUBLE) IMPROVEMENTS



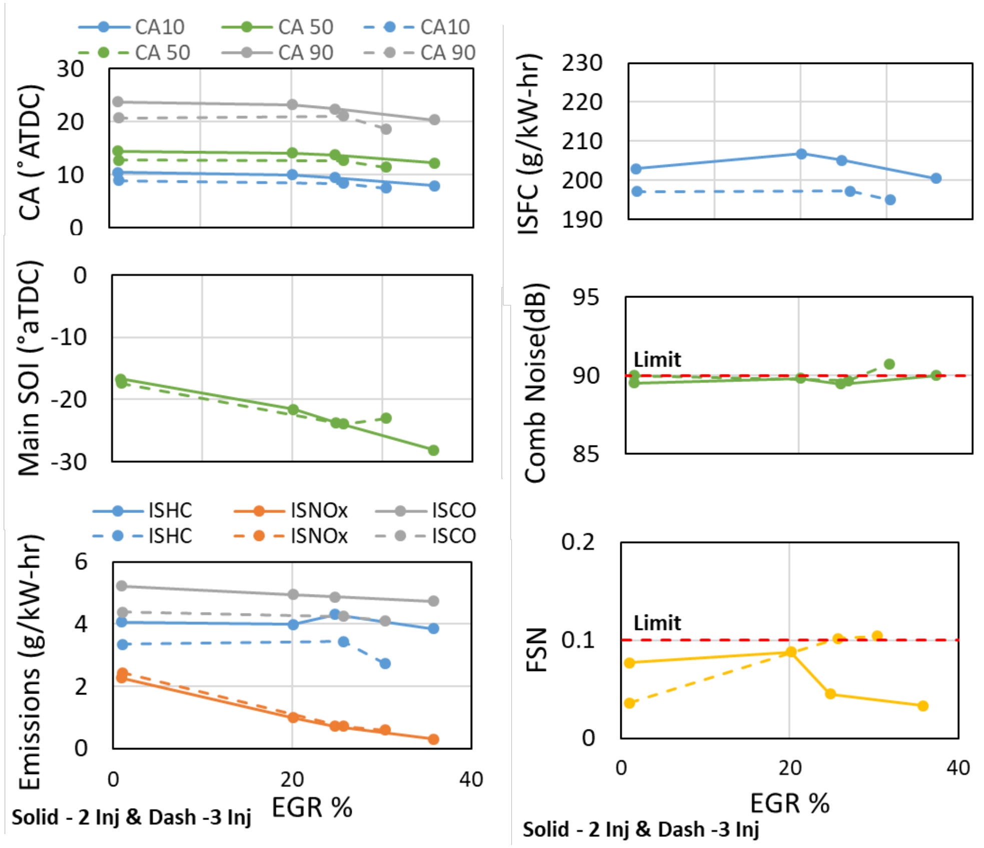

- A third injection was added shortly after the main injection
- The pilot duration remained 0.3 ms, but the main injection duration was reduced
- As a result, the main injection timing could be advanced for the same combustion noise, advancing the combustion phasing
- NOx emissions were similar, but HC, CO, and ISFC all reduced compared to the single and double injection strategies




| gIMEP/Speed | 6 bar/2000 rpm |
|---|---|
| Tin/Pin(a) | 50 °C/1.44 bar |
| Injection | Single/Double/ Triple |

# EGR $NO_X$ REDUCTION

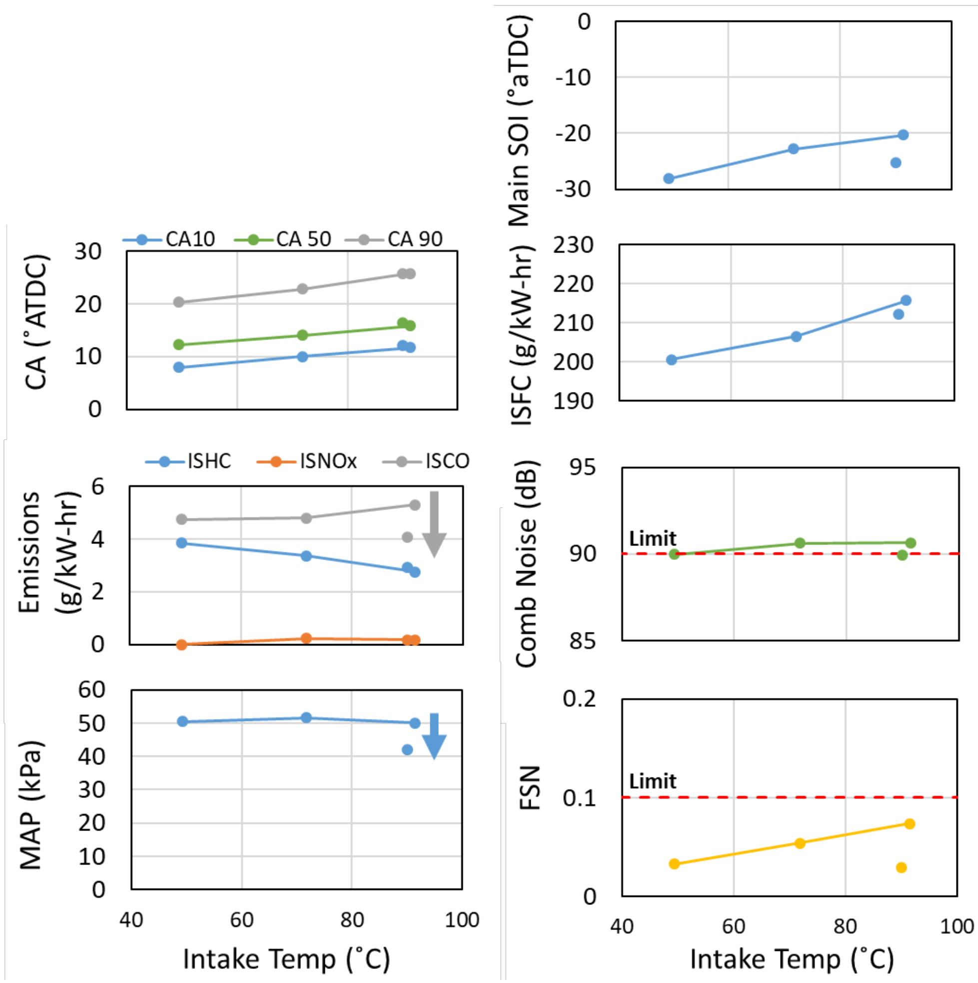
- Without EGR, ISNOx emissions were ≈2-3 g/kWh
- With 30% EGR, ISNOx decreased to 0.6 g/kWh and to 0.3 g/kWh with 35% EGR
- For the same combustion noise level, the new triple injection strategy had earlier autoignition (CA10) and combustion phasing (CA50)
- Throughout the EGR sweep, triple injections (double late injections) had lower ISHC, ISCO, and ISFC




| gIMEP/Speed | 6 bar/2000 rpm |
|---|---|
| Tin/Pin(a) | 50 °C/1.44 bar |
| Injection | Double/Triple |

# TEMPERATURE TO REDUCE HC AND CO EMISSIONS

- Intake air temperature was increased to raise the cylinder temperature, simulating exhaust rebreathe or NVO
- Increased temperature reduced HC emissions, but combustion phasing needed to be retarded to maintain CN
  - Resulting ultimately in higher ISFC
- Simultaneous increase in temperature and reduction in boost pressure gave the best combination for lower ISCO and ISFC
  - Interesting that ISCO was reduced, but not ISHC




| gIMEP/Speed | 6 bar/2000 rpm |
|---|---|
| Pin(a) | 1.5-1.4 bar |
| Injection | Double/Triple |

# RESPONSES TO 2017 AMR REVIEWER COMMENTS

- **Reviewer Comment**
  - *"Parametric sweeps of start of ignition (SOI), split ratio, injection pressures, and exhaust gas recirculation (EGR) rates is an excellent way to provide better understanding of GCI fundamentals and how to improve performance"*
    - Work carried out in 2018 focused on parametric sweeps of these parameters while holding combustion noise level constant
  - *"…the attribute constrained efficiency is quite poor…"*
    - Work this year improved the attribute constrained efficiency (emissions, CNL, stability) by showing a drop in ISFC from 210-215 to 195-200 g/kWh
  - *"…any collaboration with a LD OEM that is willing to put GCI in to production"*
    - Discussions with Volvo and Steve Ciatti had led to them providing a new Volvo LD diesel engine platform to upgrade to. However, this engine will not fit into the ACEC LD LTC multi-mode guidance.

# COLLABORATIONS

- **GM**: Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- **Eaton:** Supercharger support, boosting guidance

- 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

# REMAINING BARRIERS AND CHALLENGES

- Minimum swirl in most LD diesel engines likely too high for GCI
- Part-load combustion stability with limited boost or temperature increase
- Identify the ideal mixture stratification for emissions, CN, and efficiency across the engine operating map
- Identify most efficient method to reduce and control part-load HC and CO emissions (injection, trapped residual, etc.)
- Control low FSN at high load (>14 bar BMEP) while keeping noise low (<95 dB)
- Expand stable LTC operating region
- Examine CR as influence for Combustion Noise/BSFC tradeoff
- Strategy for low cold-start emissions

# PROPOSED FUTURE WORK

- Transition full-time GCI research to Argonne's HD Caterpillar single-cylinder engine
  - Lower CN restrictions, higher efficiency/operating range potential
  - Low swirl rates, beneficial for fuel stratification
  - Large bore size reduces fuel impingement limitations
- Could be applicable to on-road or off-road applications
- Add fuel flexibility for the MD/HD market (gasoline or diesel)
  - Initial focus on 87 AKI E10 gasoline
- Update from HEUI to modern common-rail injection equipment
- Baseline engine on diesel fuel with guidance from Caterpillar
- Establish HD GCI emissions and combustion noise targets
  - Emissions will be based on existing HD diesel aftertreatment
  - Combustion noise limits higher than LD
- Full-time GCI approach to use LTC at low-mid loads and gasoline diffusion combustion at mid-high loads
- Explore the highest practical load range of LTC and lowest load range of gasoline diffusion combustion with multiple geometric compression ratios
- Objectives:
  - Reduced PM emissions compared to diesel combustion for the same NOx emissions
  - As high, if not higher, efficiency than diesel combustion



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

# SUMMARY

**Relevance: Support DOE LTC research through a better understanding of the physical and chemical characteristics of GCI combustion for high efficiency and low emissions**

- Approach:
  - Developments during the past year have led to a shift in the ACEC TT roadmap recommendations, LTC in a multi-mode operation with SI combustion
  - Being CN is the most restrictive parameter for higher efficiency, parametric sweeps were performed at a constant 90 dB CNL
- Technical Accomplishment:
  - Constant CNL sweeps of injection parameters led to an injection strategy where the double-injection occurs near TDC rather than earlier in the compression stroke
  - While meeting all emissions, stability and noise targets, ISFC was reduced compared to previous years
- Future Work:
  - A HD platform and has been identified for full-time GCI research
  - The approach will work to expand LTC operation at low-mid loads and utilize gasoline diffusion combustion at mid-high loads

## THANK YOU FOR YOUR ATTENTION!

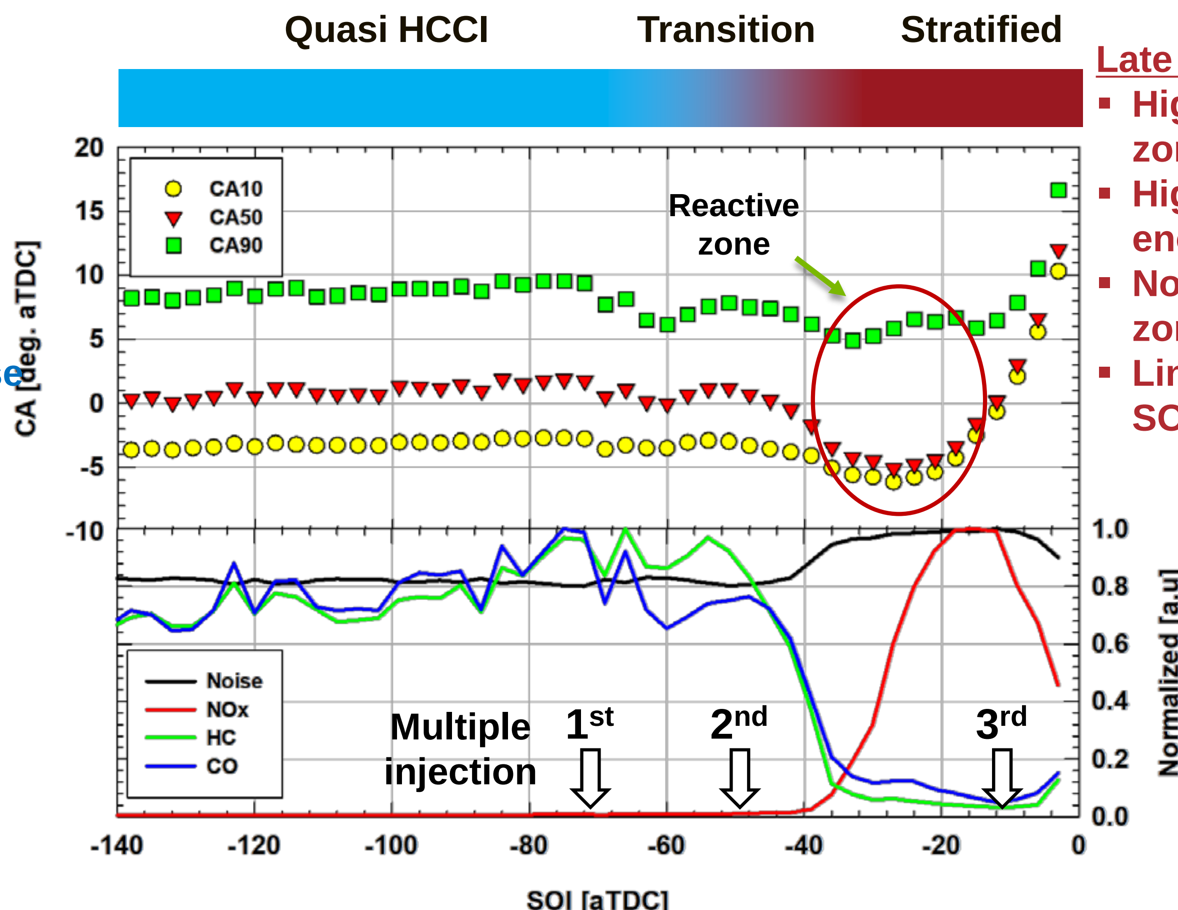
## QUESTIONS?

# TECHNICAL BACK UP SLIDES

# APPROACH FOR GCI TO TARGET HIGH LOAD OPERATING CONDITIONS: LESSONS LEARNED FROM PREVIOUS SOI SWEEP (SINGLE INJECTION WITH CONSTANT LAMBDA)

Early injection
- High HC/CO
- Low FSN
- Chemical control of autoignition & combustion phasing
- Combustion noise (premixed)

Parameter to control:
- EGR
- P_intk
- T_intk
- Split ratio




Late injection
- High NOx (reactive zone)
- High FSN if not enough mixing
- Noise (reactive zone)
- Linear relationship SOI vs. CA50

Parameters to control:
- SOI
- Injection pressure
- Nozzle design
- Swirl
- Split ratio

- Single injection is not ideal for wide load range: noise vs. FSN; emission trade-off
- Conceptual understanding for multiple injection strategy (i.e. triple injection):
  - 1st injection: -141 to -70 aTDC; limited in amount of fuel due to noise (early auto-ignition)
  - 2nd injection: -70 to – 30 aTDC; help transiting from premixed to heavy stratified combustion
  - 3rd injection: -30 aTDC or later; provide control for combustion phasing

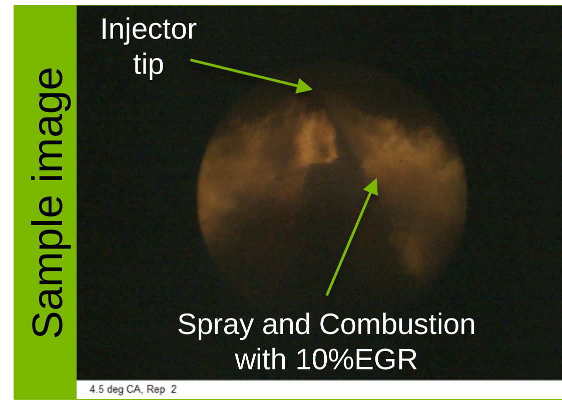


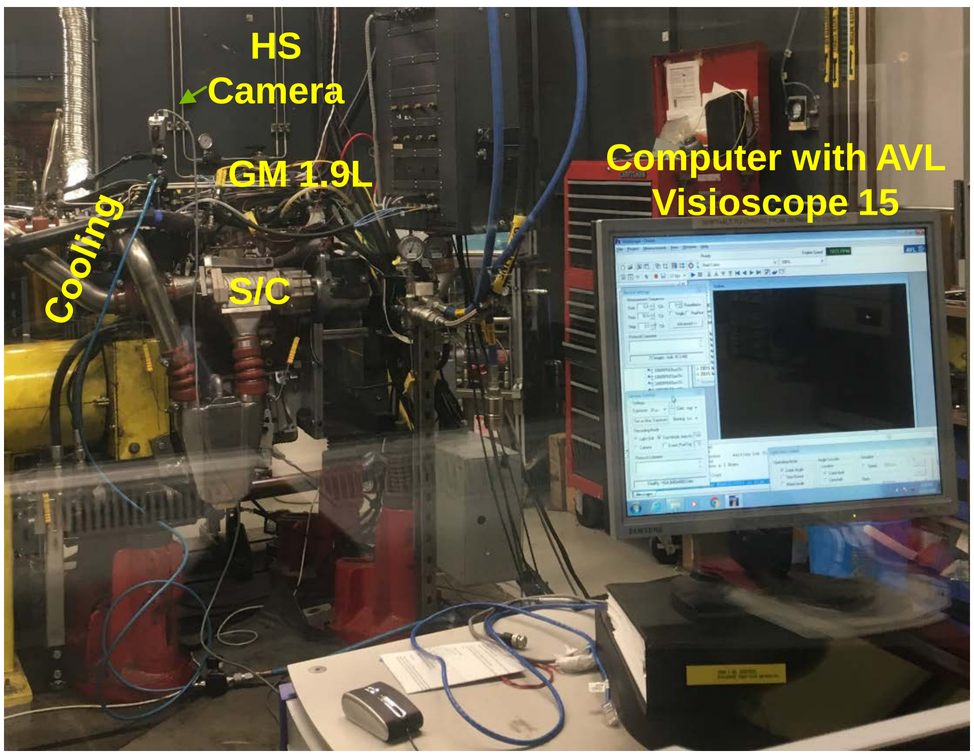
Argonne NATIONAL LABORATORY

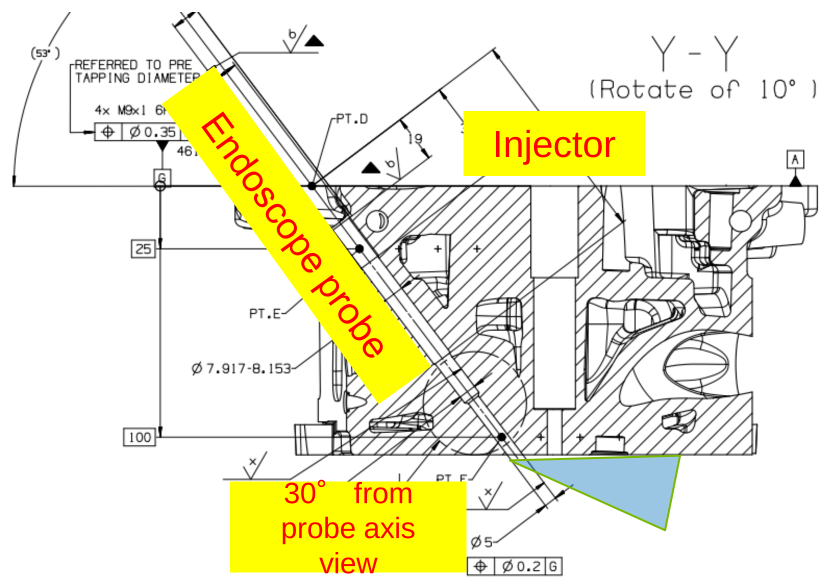
# ENDOSCOPE IMAGING SETUP: COMBUSTION LUMINOSITY

| Camera | PixelFly |
|---|---|
| Frame rate | 10 Hz |
| Exposure | 5-20 µs |
| Pixel size | 680 x 480 |
| Interval | -5° to 30° aTDC |

- Endoscope access in cylinder #4
- Covering complete combustion event
- Spray (some scattering) is visible for 2nd injection

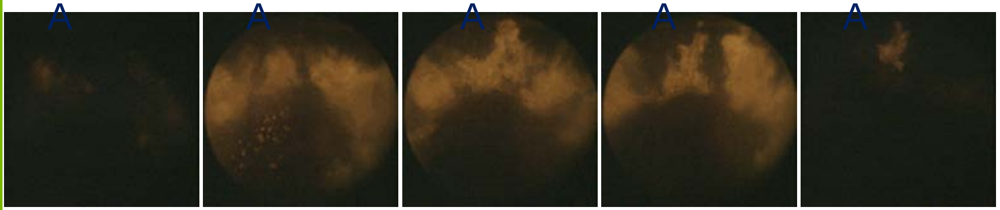


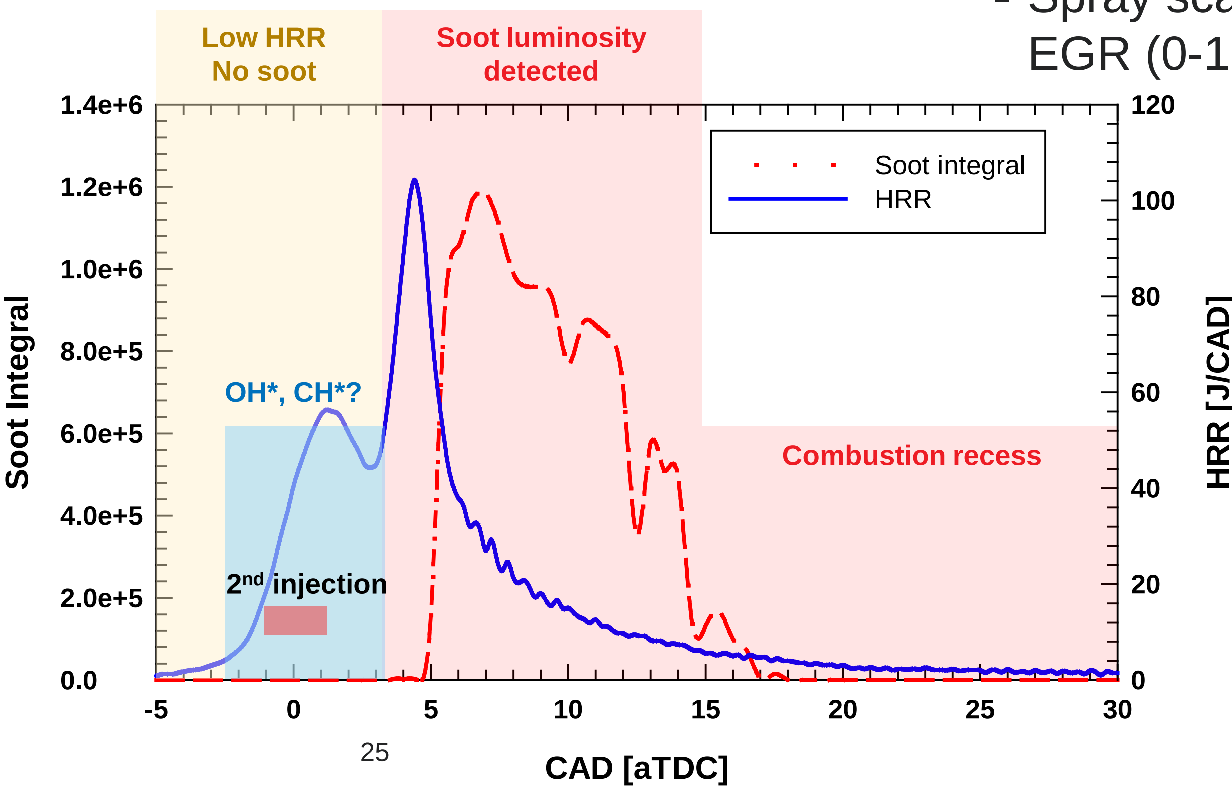



# ENDOSCOPE IMAGE TO INVESTIGATE SPRAY AND COMBUSTION OF GCI: CORRELATION OF SOOT LUMINOSITY AND HRR

3° CA 5° CA 10° CA 13° CA 20° CA



- Soot luminosity is still visible even with FSN measured of 0.053
- Soot NOT appear at low HRR region
- Combustion ends long (~30 aTDC) after EOI
- Spray scattering were seen at lower EGR (0-10%) cases




| Baseline condition | |
|---|---|
| EGR [%] | 20 |
| 600 bar, Double injection<br>-50 aTDC/~TDC with ~55:45 ratio | |
| Boost Pressure [bar(a)] | 1.4 |
| Intake Air Temp [°C] | 55 |
| Global λ (= 1/Φ) | 1.8 |