Use of Low Cetane Fuel to Enable Low Temperature Combustion

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Project ID# ACE11

Overview

Timeline

- Started May 2008
- Ends Sept. 2012
- 60% Complete

Barriers

- Barriers addressed (from MYPP)
  - Fundamental combustion R&D
    - "Investigation of advanced combustion system concepts that enable high efficiencies and fuel injection strategies for the implementation of advanced combustion systems"
  - Engine Systems and Technologies R&D
  - Engine System Integration

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY10 $670k
  - FY11 $670k

Partners

- Argonne is project lead
- Partners are
  - GM Europe and GM R&D
    - Monthly teleconferences. Occasional site visits
    - Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
  - University of Wisconsin-Madison
    - Graduate student performing gasoline-fueled engine simulations using KIVA
  - BP
    - Several different cetane number fuels,
  - Drivven, Inc.
    - Controller algorithm upgrades

Objectives of this Study (Relevance)

- Focus upon gasoline-like (low cetane) fuels
  - Avoid soot/NO_x production by insuring the end of injection occurs before the start of combustion
  - Fuel/(Air+EGR) will be premixed, but not well mixed – some stratification will enable higher load operation and control of combustion phasing
- Maintain high power densities (~15 bar BMEP) while retaining high efficiency (30-40% over entire range) and low emissions
- Control combustion phasing by utilizing in-cylinder controls
  - Injection timing, pressure, number of injections influence combustion phasing
  - EGR is well distributed with new mixing configuration
  - Use pressure transducer and other sensors for feedback control, if needed
- Determine boundaries of operation by using endoscope imaging

Milestones

- Exploration of gasoline injection strategies — Jul 2010
- Design of Experiments analysis — Aug 2010
- Reconfiguration of EGR valve — Sep 2010
- Operate 75 RON and 65 RON gasoline — Oct 2010
- Install/commission new dynamometer controller — Jan-Mar 2011
- APS gasoline operation with Bosch injectors — Feb 2011
- UW-ERC simulation of gasoline engine data — Mar 2011

Future milestones

- Injection and EGR sweeps for 4 operating points — Jun 2011
  - Sensitivity study for these inputs
  - Use different injection inclusion angles
    - 148 degree standard, 135 and 120 degree available
- Use FACE fuels 1 and 3 to validate ERC models — Sept 2011
  - Low cetane, high volatility, both low and high aromatic
- Develop gasoline operation engine strategy — Nov 2011

Approach

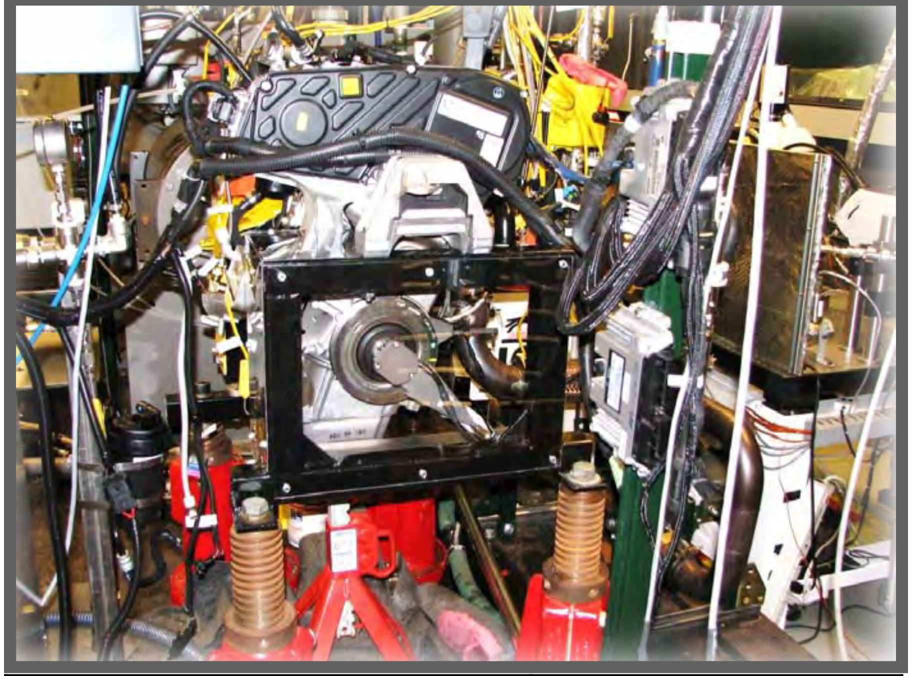
- This project will use low cetane/high volatility fuel
  - Fuel provided by BP Naperville
  - Significantly increase ignition delay
  - Limit/eliminate wall and piston fuel wetting
  - Desired ignition after the end of injection to avoid mixing controlled combustion
  - This approach is different than most other LTC projects!
    - Little to no EGR, especially at low speed/load
- Lubricity additive (100 ml/drum) to insure operation of diesel injection equipment
- Use fluid mechanics (injection parameters) to control combustion phasing and engine load
- Support experimental work with engine simulations from UW-ERC using KIVA
- Leverage our APS injector work to better understand diesel injector performance using gasoline-like fuels
- Different compression ratio pistons from GM PowerTrain Europe (GMPTE) (14:1,15:1,16:1,17.5:1)

Technical Accomplishments

- Successfully operated the engine using low cetane fuels
  - 85, 75 and 65 RON gasoline
  - Instructed to focus upon 80-85 RON fuels by USCAR tech team
- Very low NO_x emissions levels achieved
- 4 target engine operating conditions
  - 2 bar BMEP at 1500 RPM
  - 5 bar BMEP at 2000 RPM
  - 8 bar BMEP at 2500 RPM
  - 12 bar BMEP at 2750 RPM
- Have successfully operating engine at 16 bar BMEP at 3000 RPM.
- Successfully achieved greater than 30% BTE for most operating points
- Design of Experiments analysis to determine input variability sensitivity
  - ***EGR, Boost and Injection Pressure - complete***
  - EGR, Injection Pressure and Timing, Injector hole inclusion angle - planned

Engine Specifications and Tested Fuels Properties

Experimental Setup & Engine Specifications



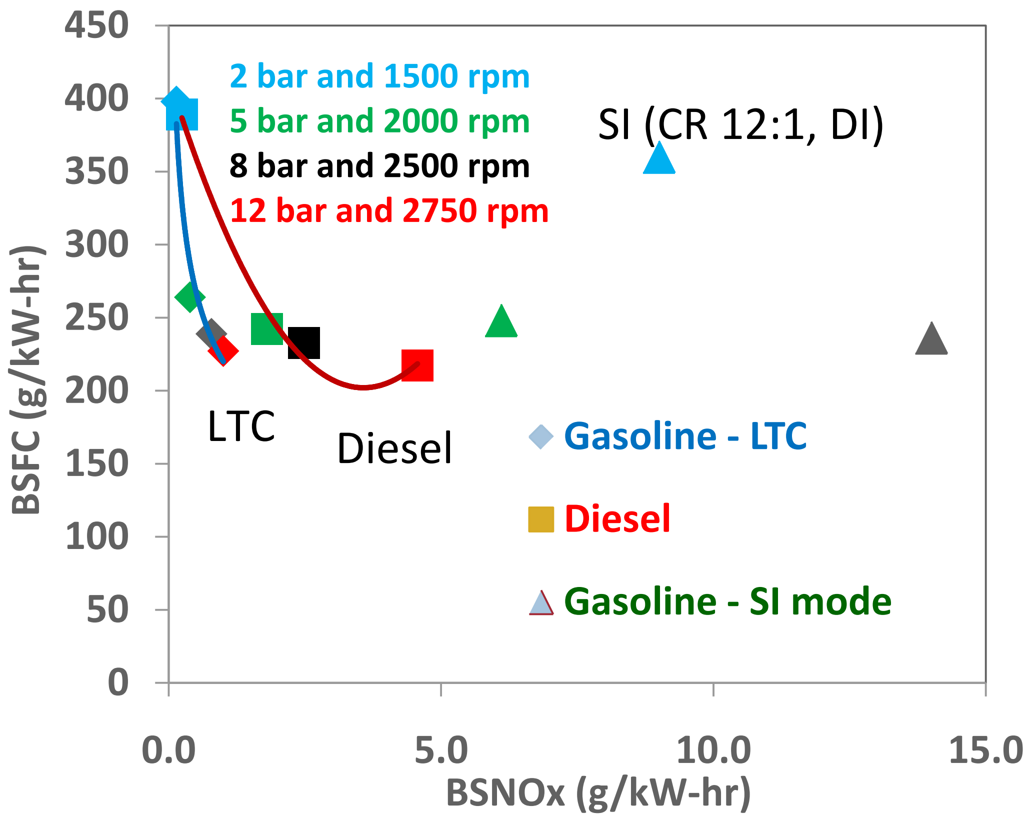
Compression ratio	17.8:1
Bore (mm)	82
Stroke (mm)	90.4
Connecting rod length (mm)	145.4
Number of valves	4
Injector	7 holes, 0.141-mm diameter

G.M 1.9 L; 110 kW @ 4500 rpm - designed to run #2 diesel ; Bosch II generation common rail injection system

Properties of the Two Tested Fuels

Property	#2 diesel	Gasoline
Specific gravity	0.8452	0.7512
Low heating value (MJ/kg)	42.9	42.5
Initial boiling point (°C)	180	86.8
T10 (°C)	204	137.8
T50 (°C)	255	197.8
T90 (°C)	316	225.1
Cetane Index	46.2	25.0

Effect on BSFC and BSNOx Emissions



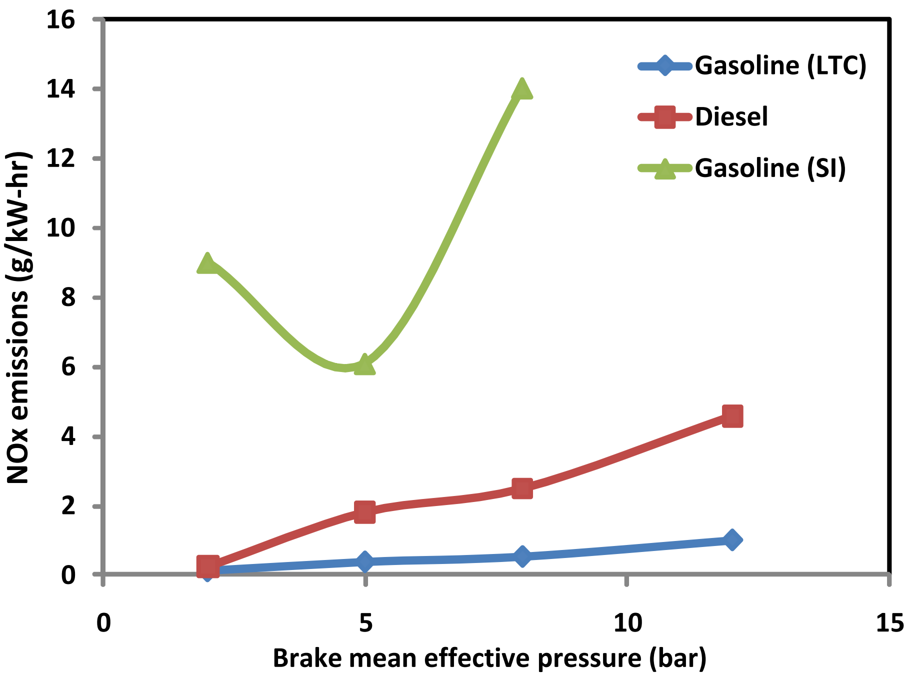
Color of the trend line reads the fuel (green – gasoline, red – diesel & blue - LTC)

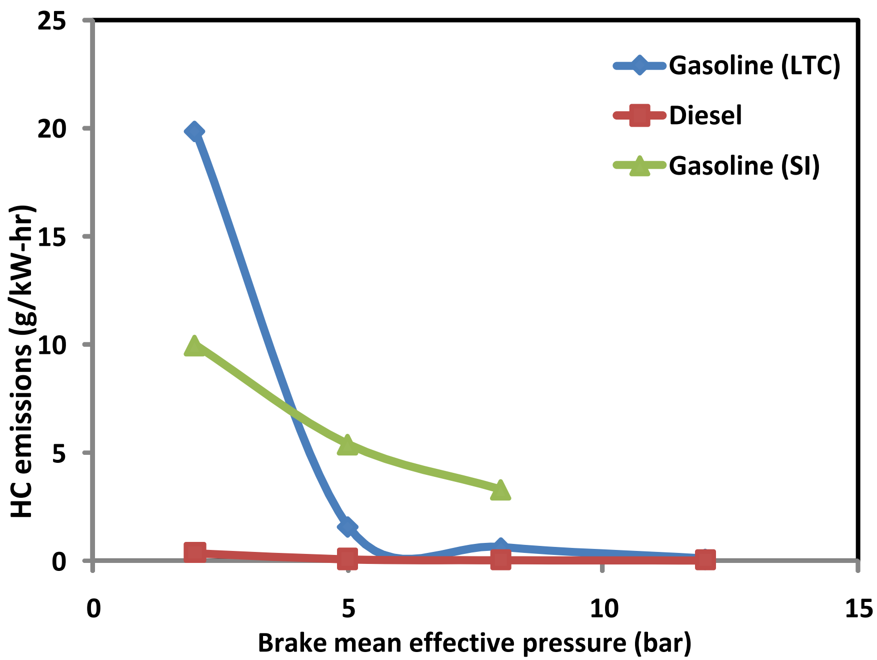
Color of the marker reads the operating condition (blue – 2 bar, green – 5 bar, black – 8 bar & red – 12 bar)

Standard gasoline operation in SI mode was referred from

Thomas Wallner, Scott A. Miers and Steve McConnell, A Comparison of Ethanol and Butanol as Oxygenates Using a Direct-Injection, Spark-Ignition Engine, 2008 ASME Spring Technical Conference ICES2008, 2008

Emissions behavior compares well with diesel baseline (NOx and HC)





Split Injection Strategies in LTC gasoline operation to optimize performance

FIRST STRATEGY (GAS-I):
First Injection - (-40°CA to -140°CA) (Partially premixed charge was prepared through this first injection)

Second injection - (0°CA) around TDC (heat release rate was maintained through this second injection)
Injection pressure - 600 bar to 900 bar (high injection pressures at higher load conditions)

SECOND STRATEGY (GAS-II):
An equal split of two early injections were employed.

First injection - (-70°CA) ; Second injection - (-25°CA).
Injection pressure - 600 bar.

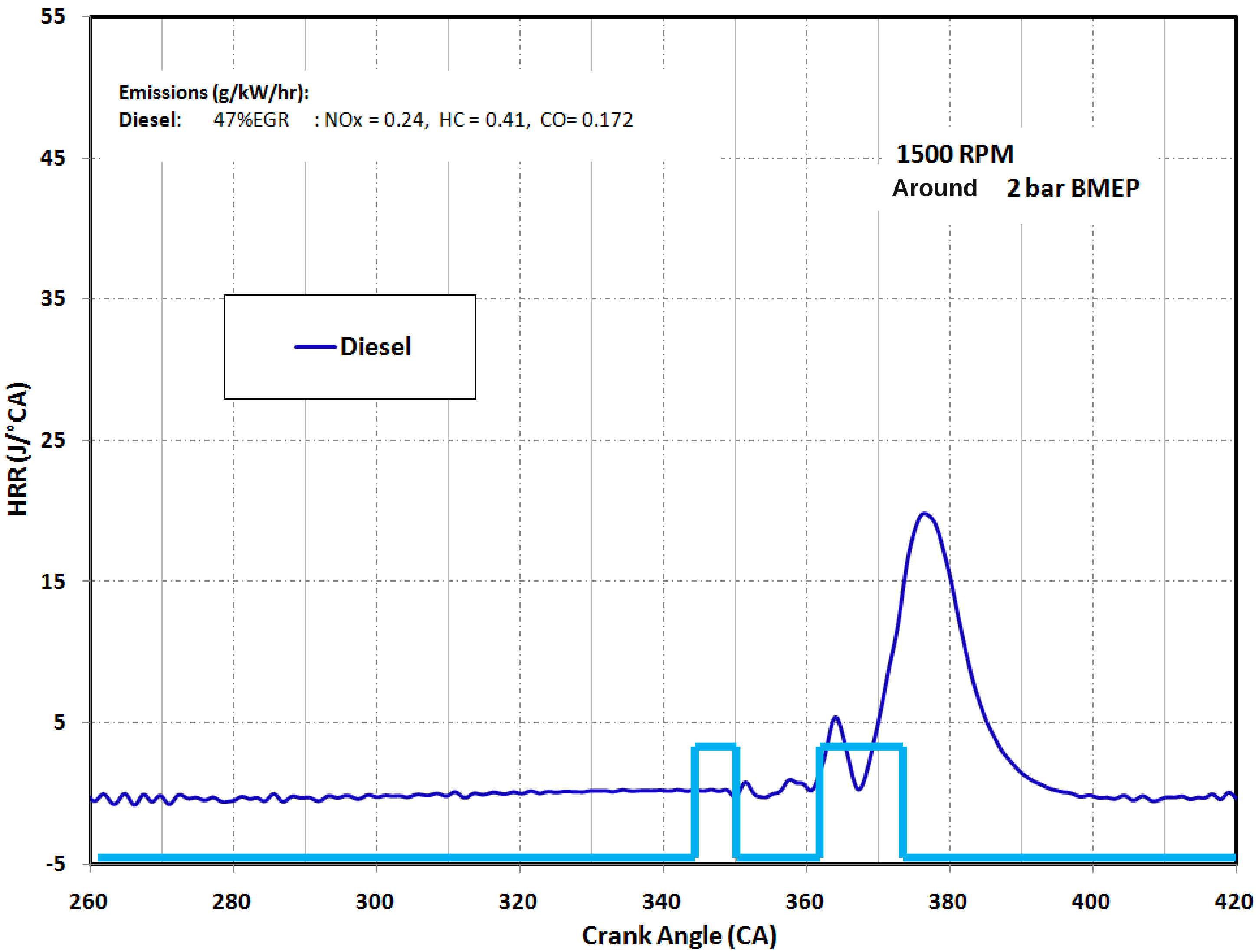
This strategy had issues of severe knocking and hunting at 5, 8 and 12 bar BMEP conditions.

THIRD STRATEGY (GAS-III):
This strategy was a refinement of the first strategy.

Very early single injection scheme (- 95°CA) – 2 bar BMEP

Equal split of an early injection and a main injection scheme - 5 bar and 8 bar BMEP conditions
Early injection - (- 60°CA to -80°CA) ; Main injection – Closely after TDC.
Injection pressure - 600 bar

Gasoline in LTC mode 1500 RPM and 2 bar BMEP



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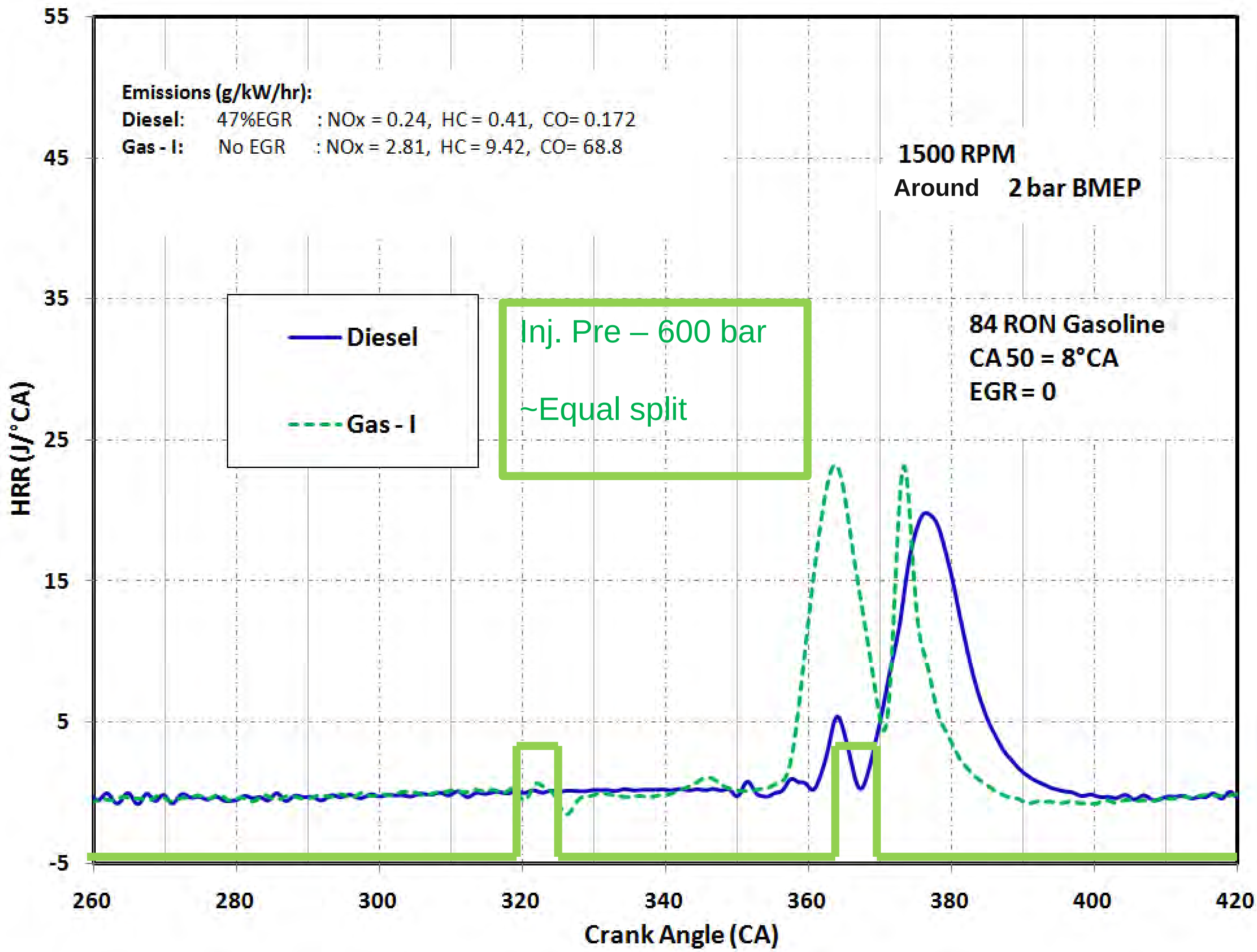

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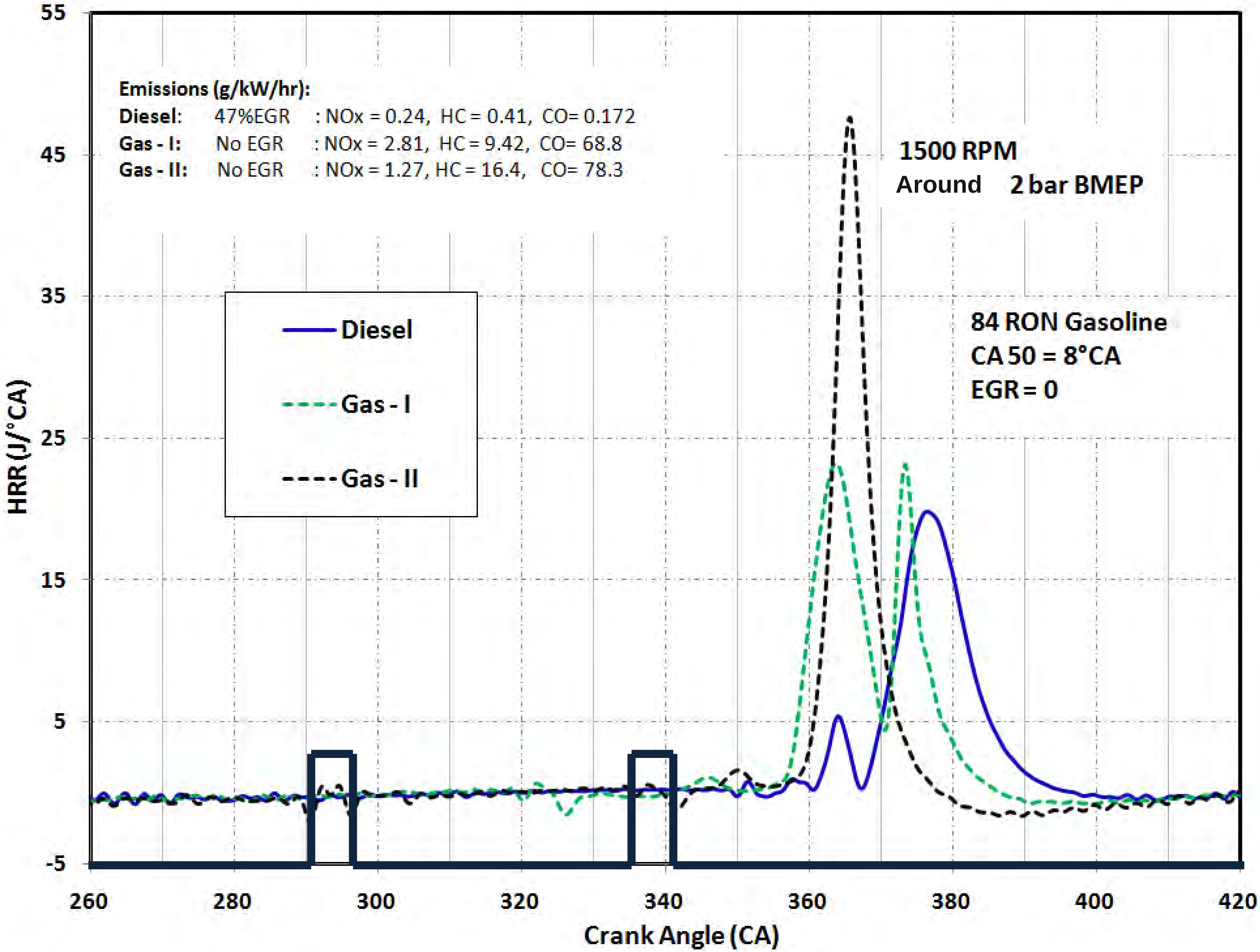

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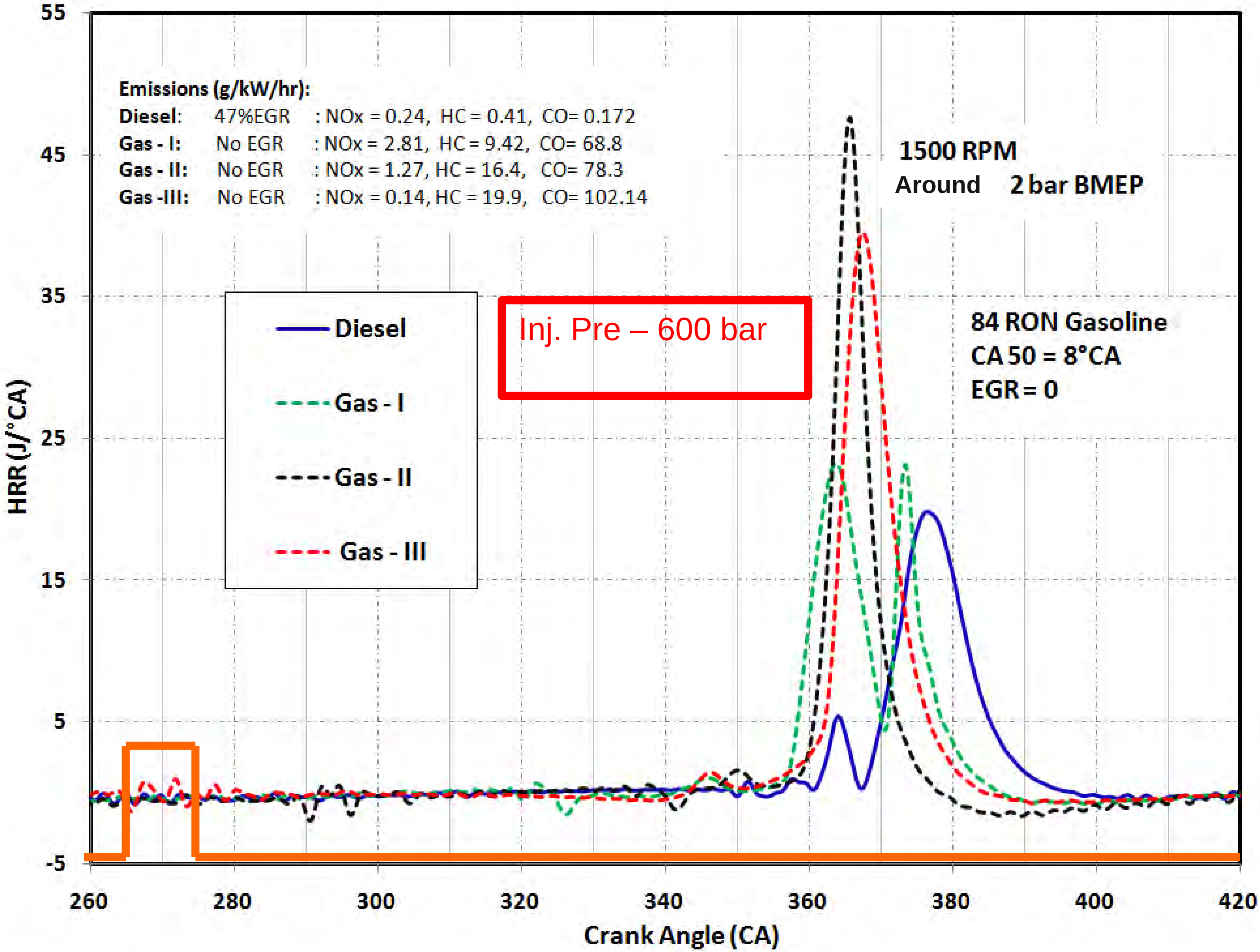
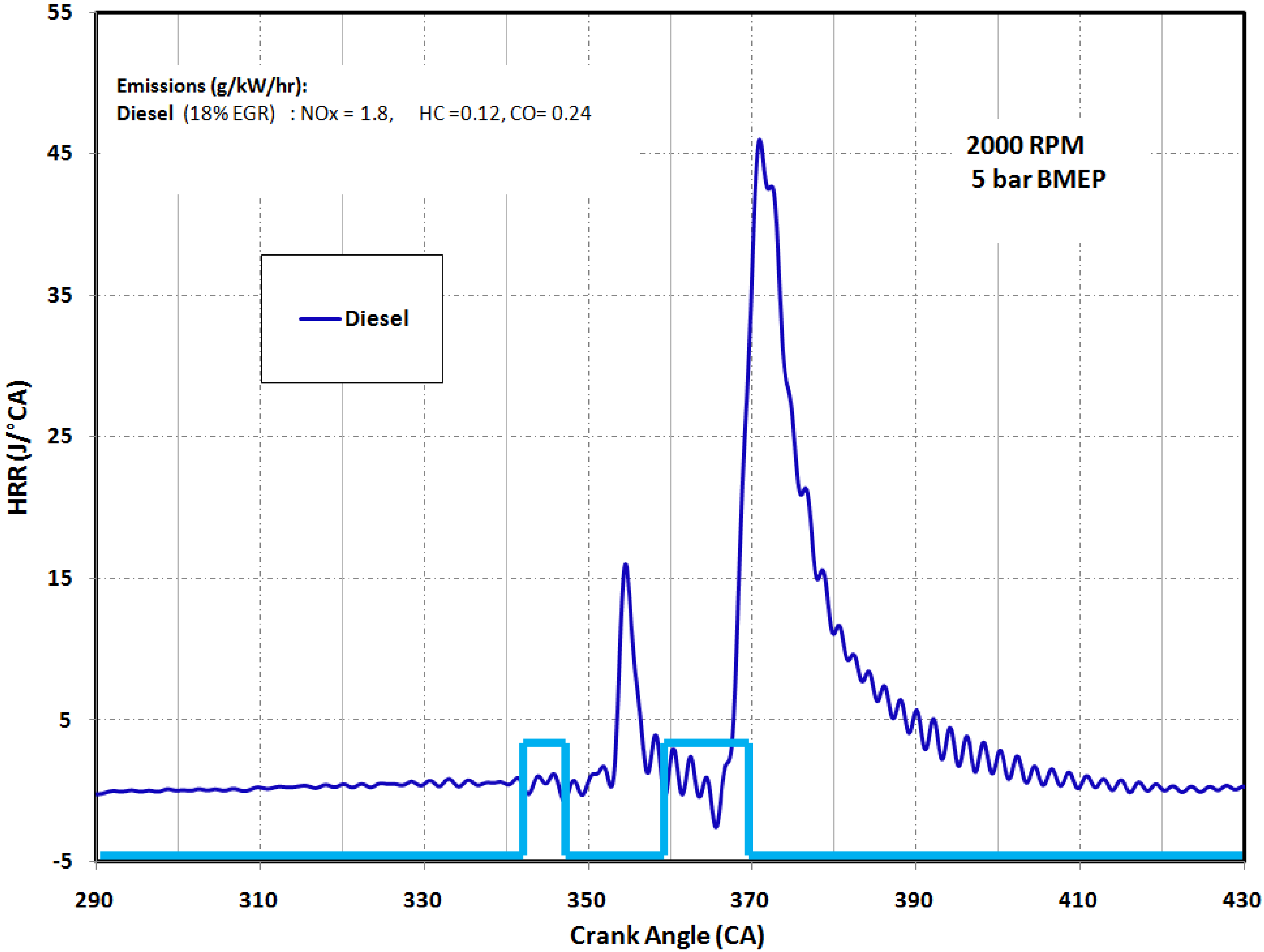


Highest EGR level with COV<5% @ 2000 RPM and 5 bar BMEP



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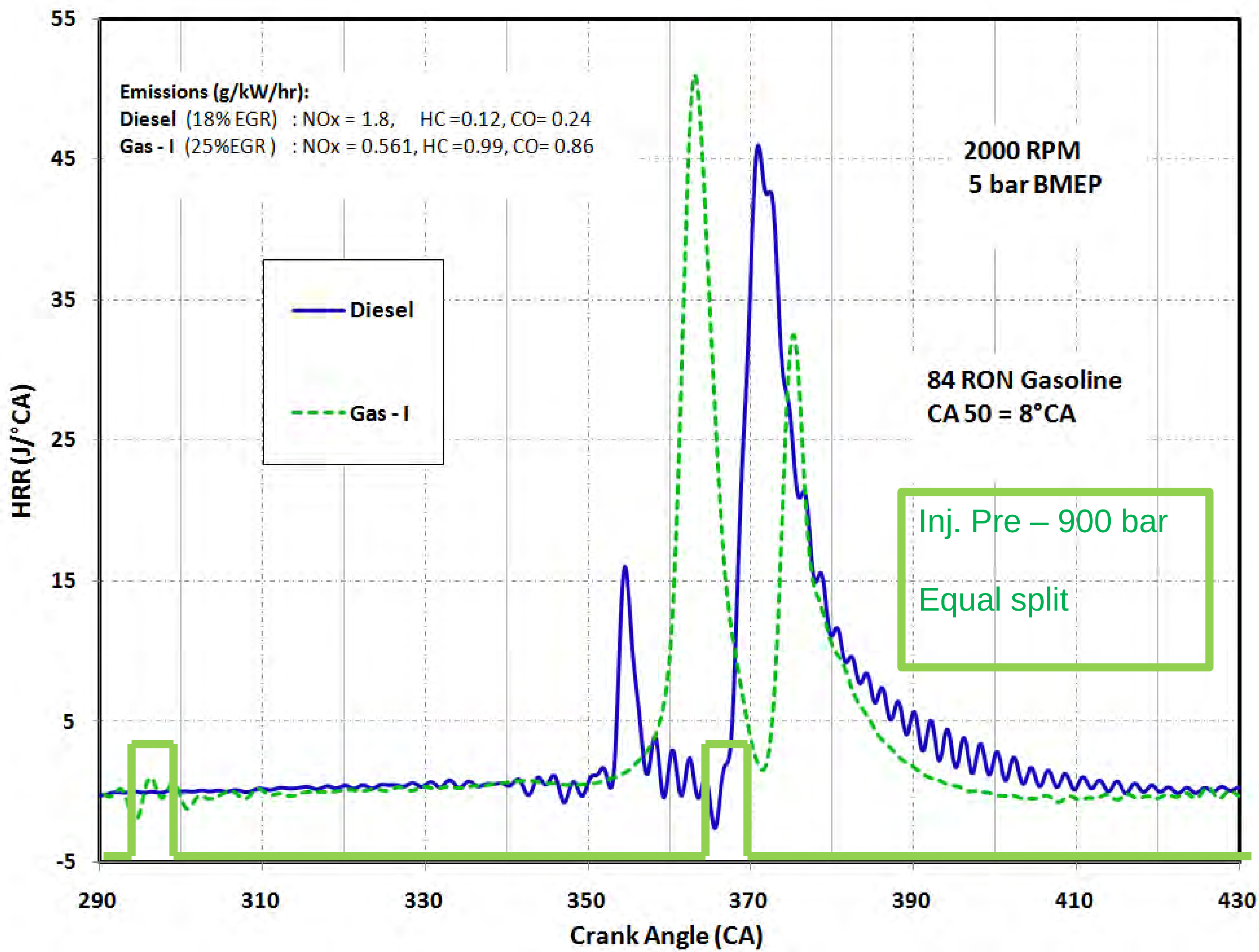

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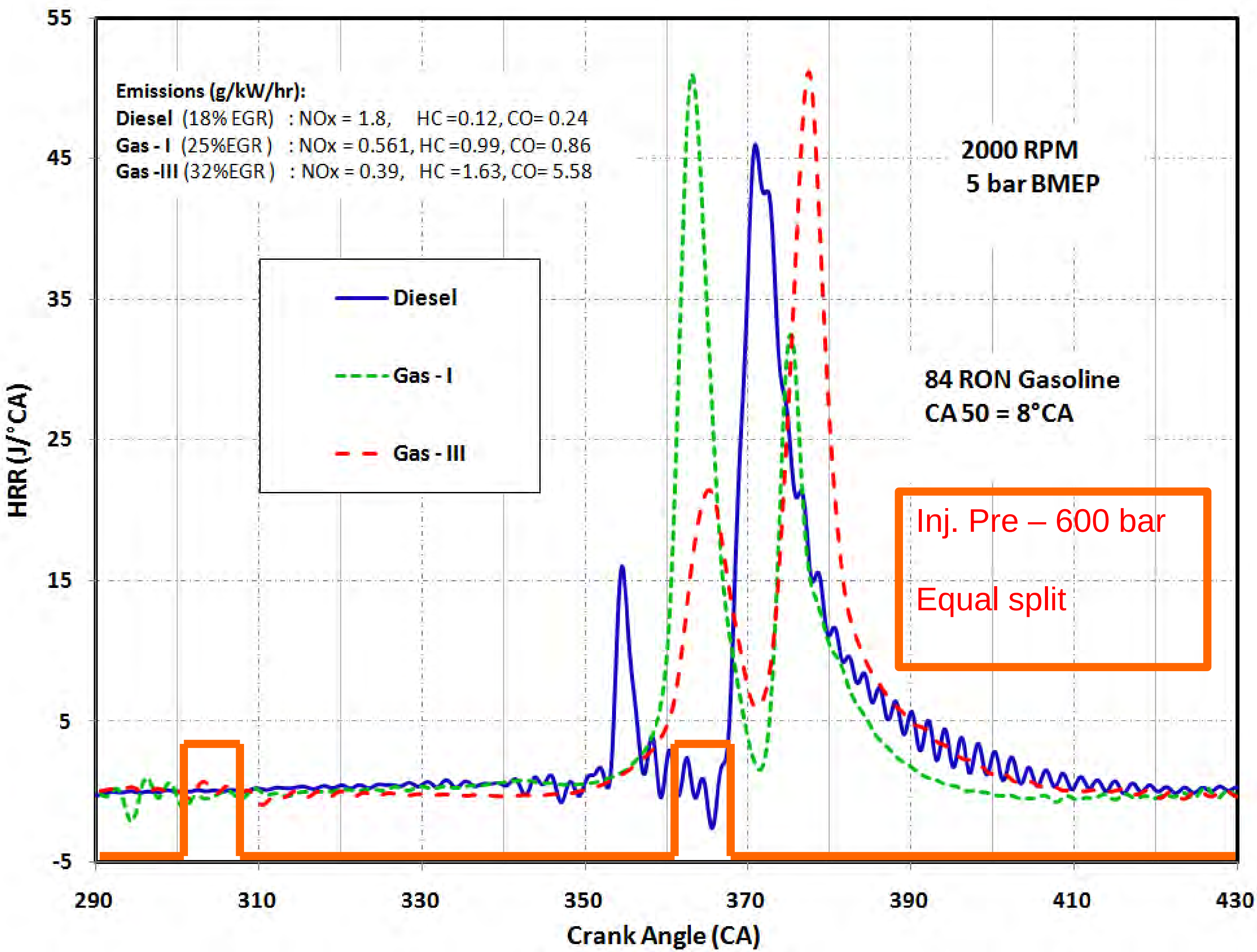
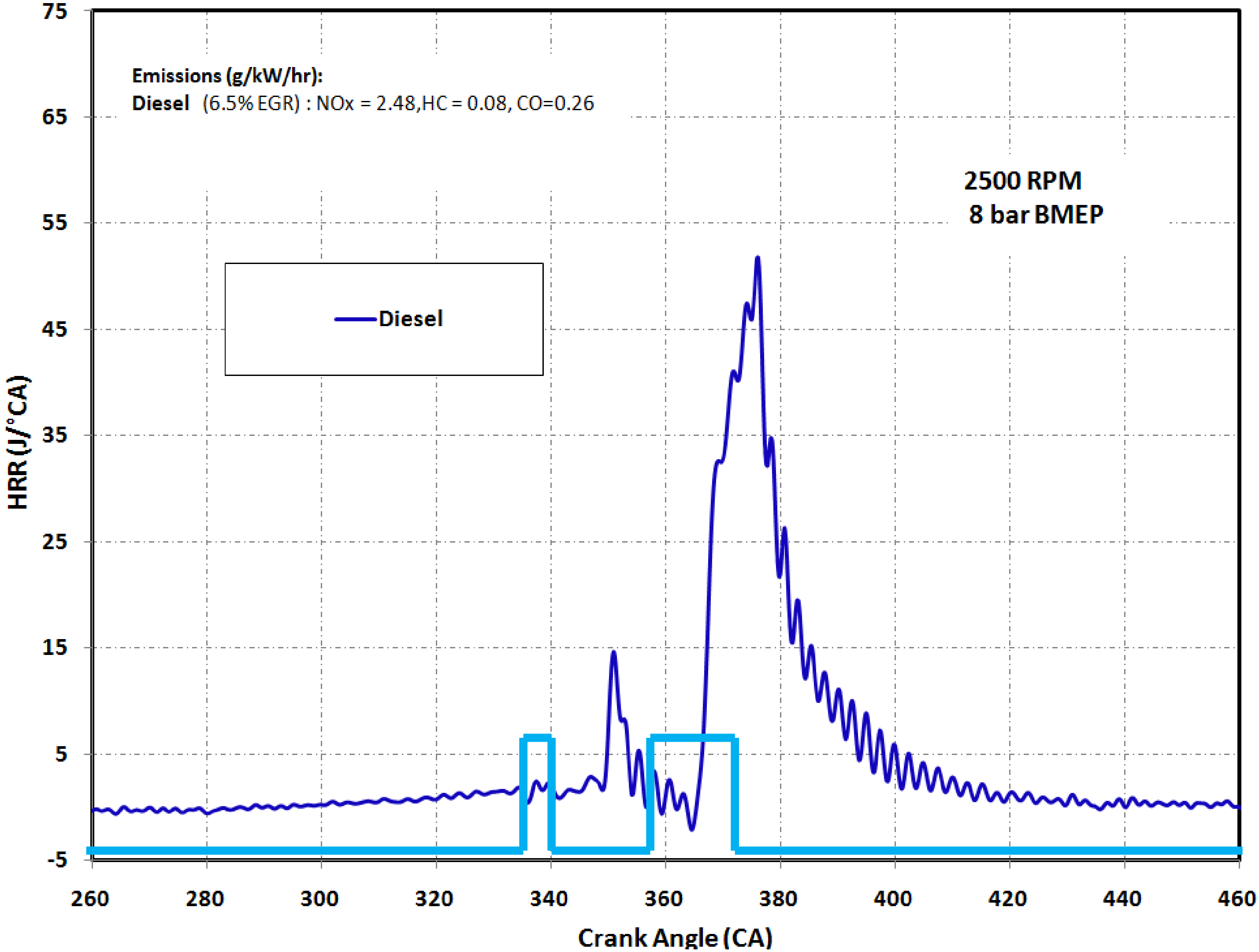


Higher speed/load conditions – 2500 RPM and 8 bar BMEP



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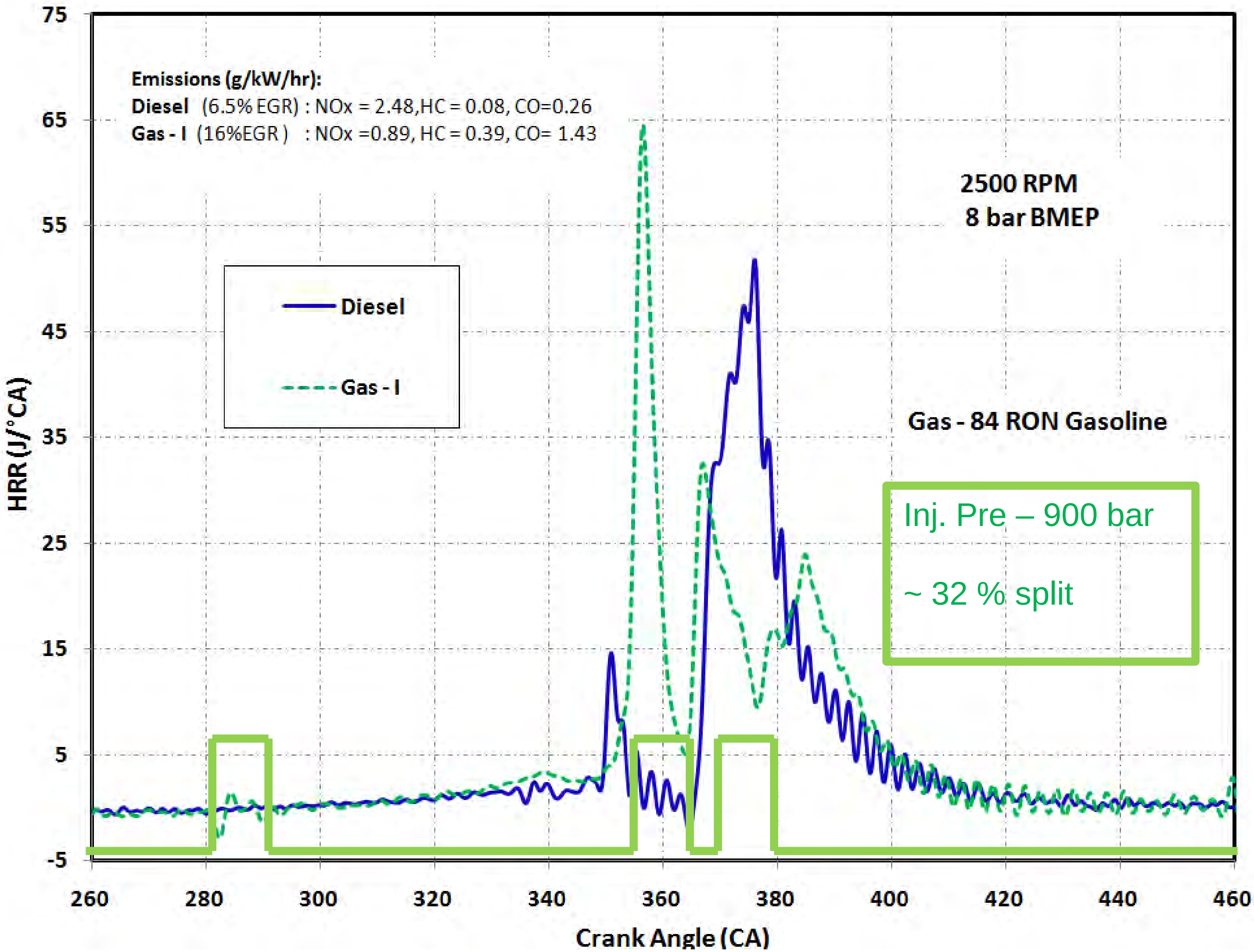

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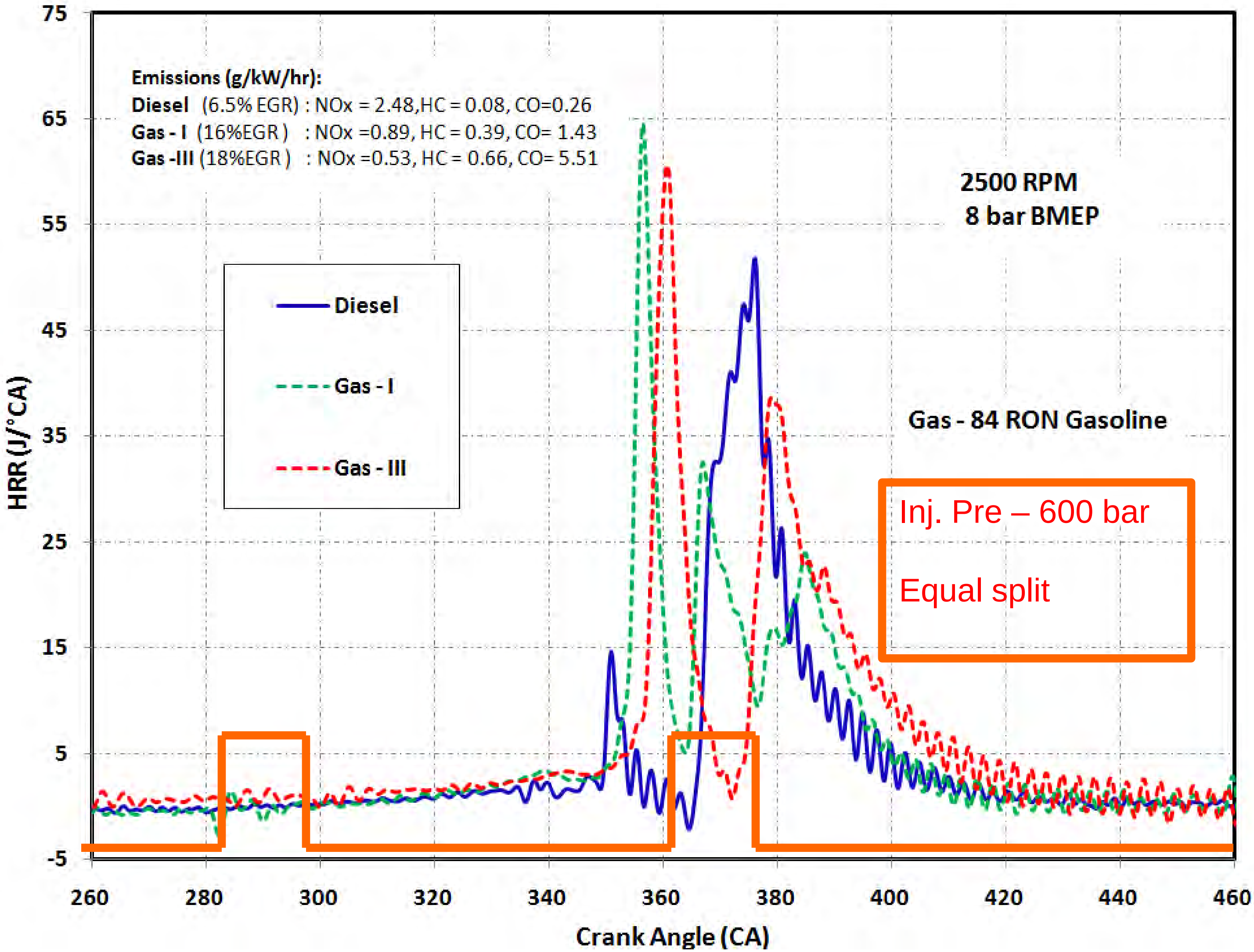
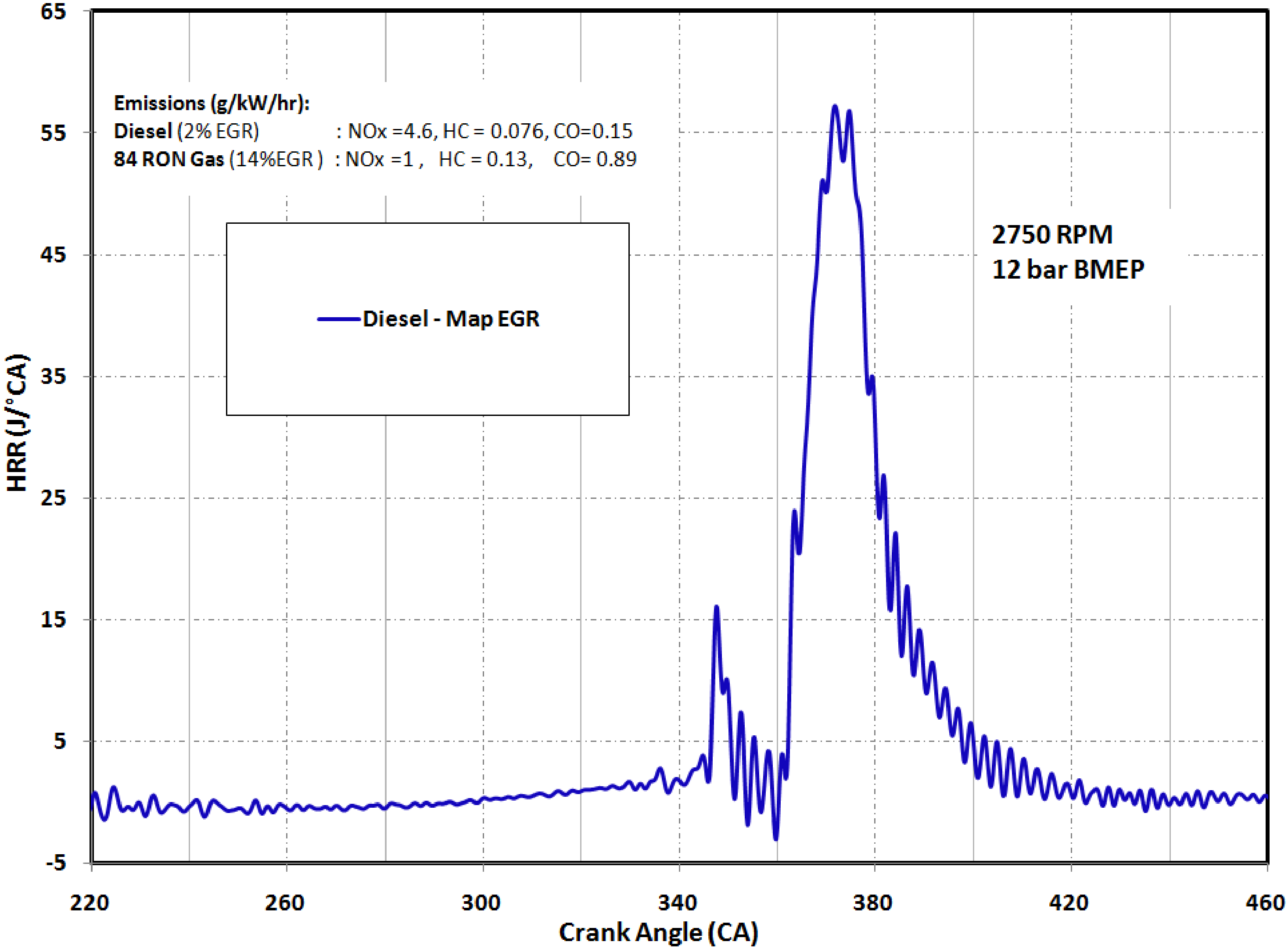


2750 RPM and 12 bar BMEP - large reductions in NOx, low HC penalty



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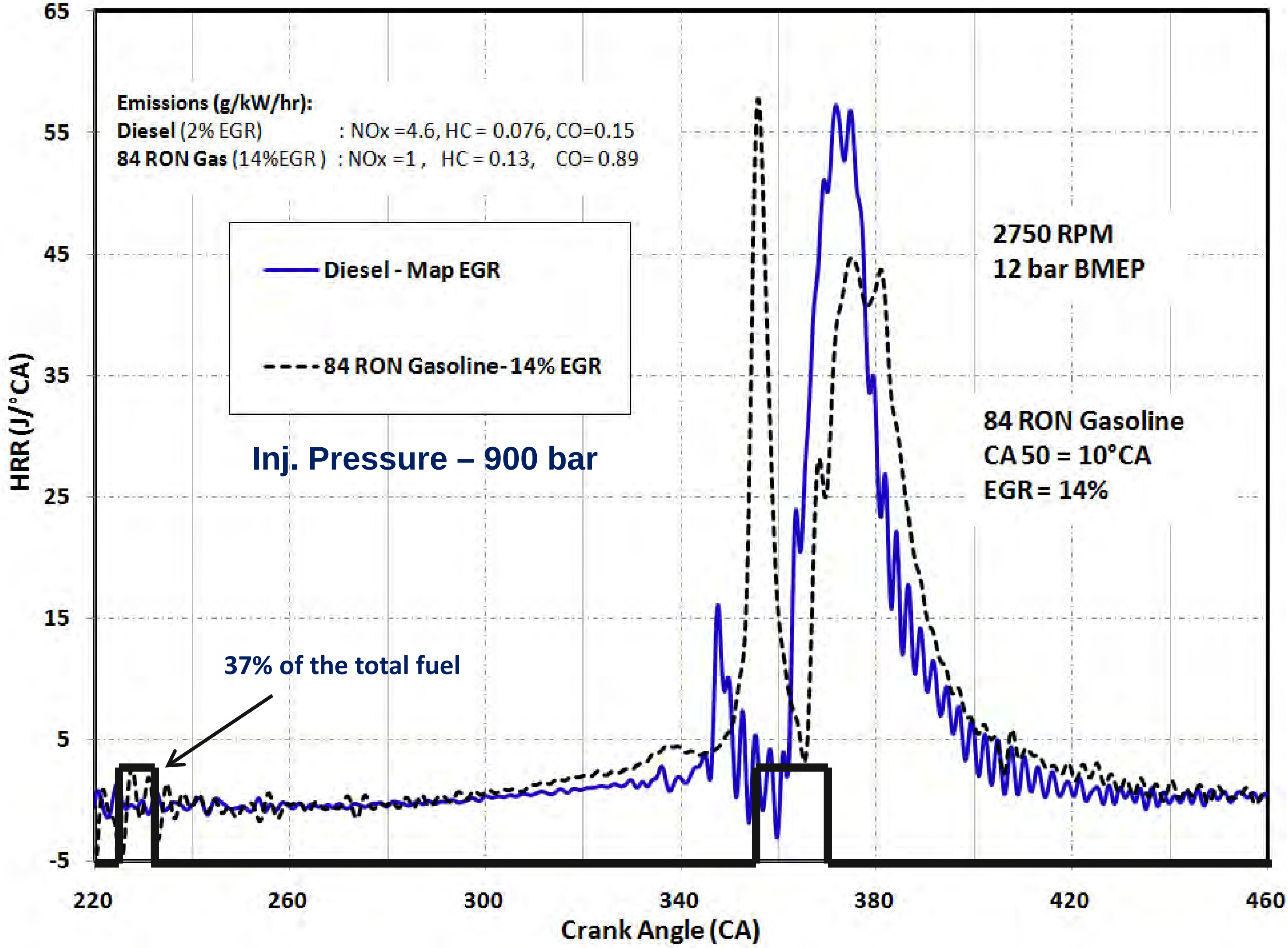
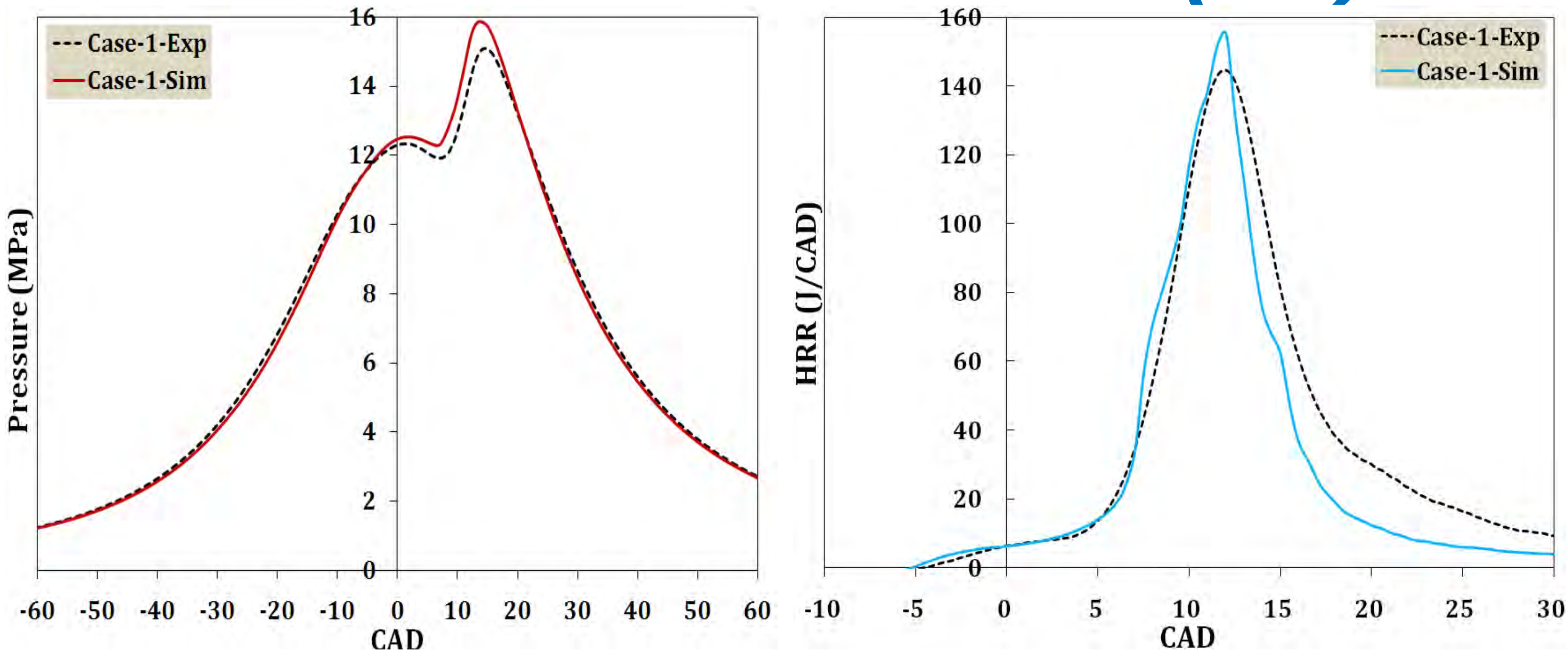


Modeling Parameters from UW-ERC

Two double injection gasoline cases are studied using the following simulation parameters taken from UW-ERC single cylinder GM engine.

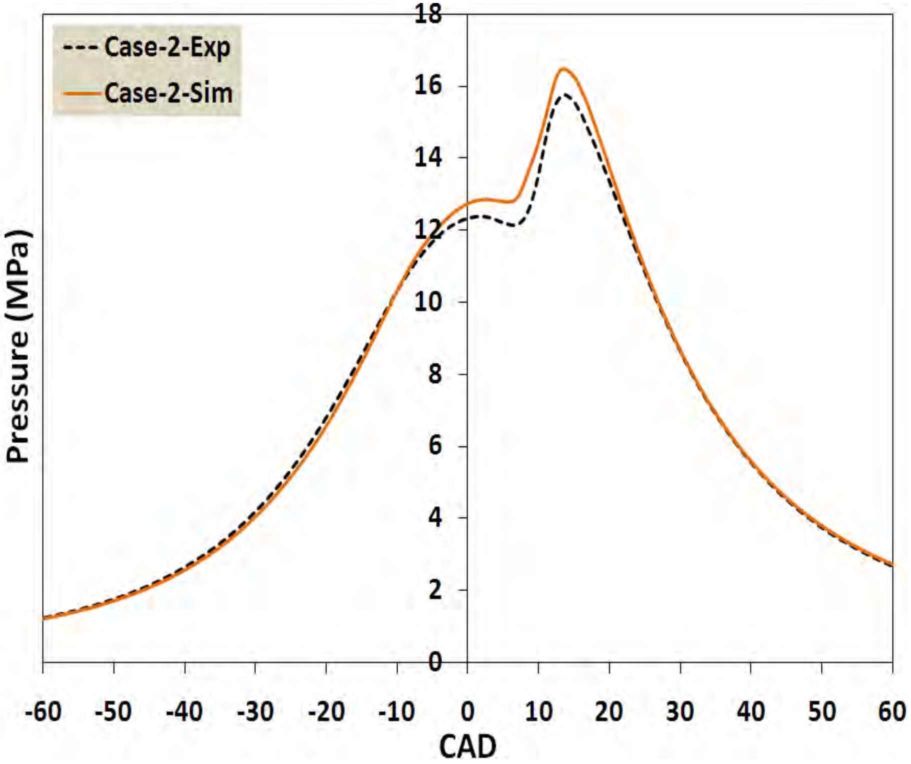
	Case-1 (55)	**Case-2 (75)**
CR	17	17
RPM	2500	2500
Initial Temperature	363	360
Initial Pressure	3.36	3.383
SOI1 (CAD)	-344.6	-344.6
EOI1 (CAD)	-335.33	-334.1
DOI1 (μs)	618	700
SOI2 (CAD)	-15.6	-11.6
EOI2 (CAD)	-3.39	-2.26
DOI2 (μs)	575	468
Fuel Flow-rate (kg/hr)	3.78	2.607

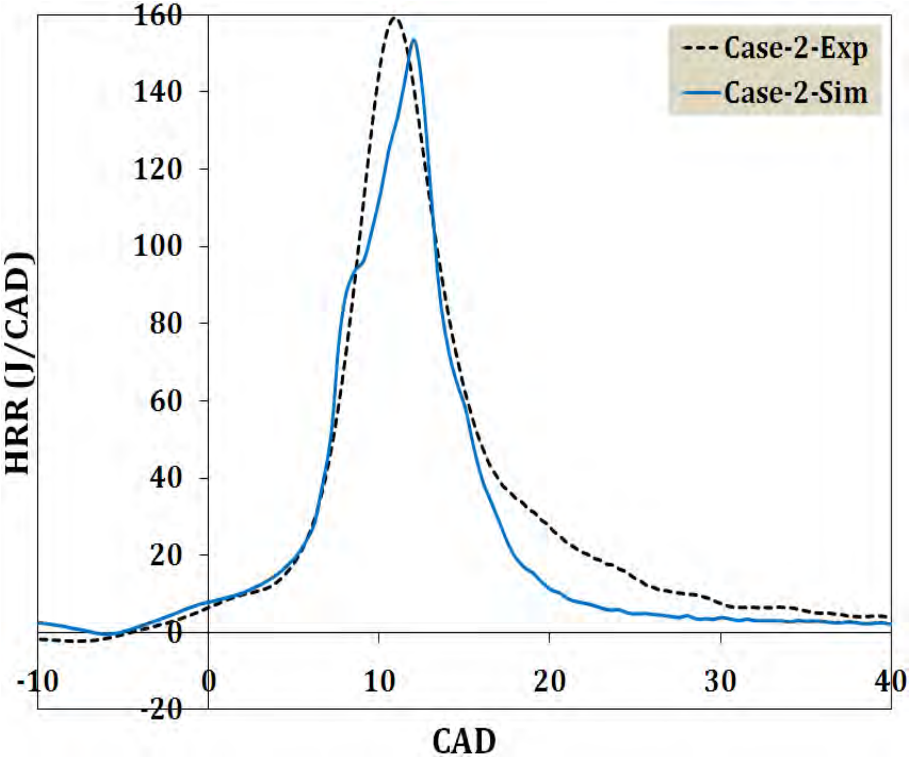
UW-ERC Gasoline Results (1/2)



The pressure trace is reasonably close to the experiment, The underestimated heat release might be due to use of the chemical heat release instead of the apparent heat release (AHRR) in the simulation.

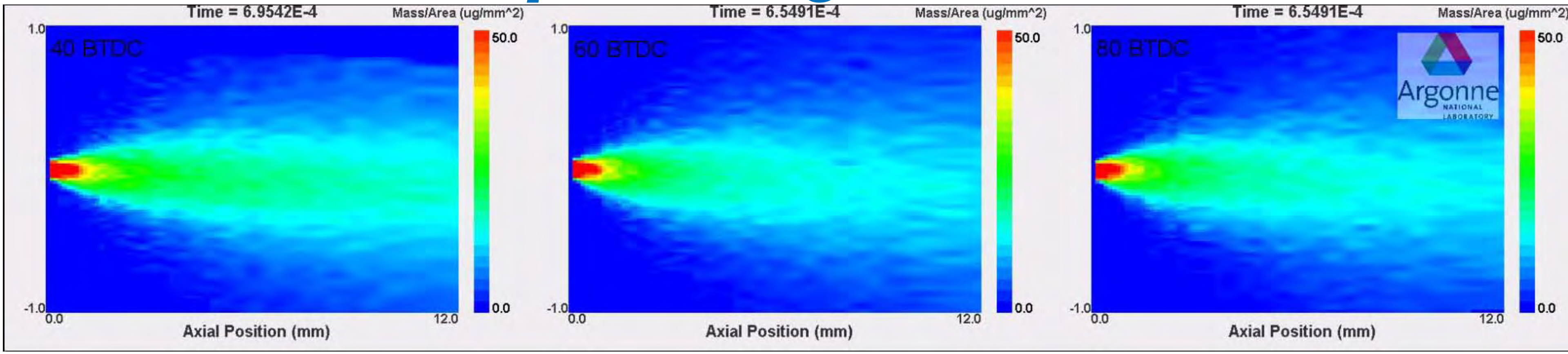
UW-ERC Gasoline Results (1/2)

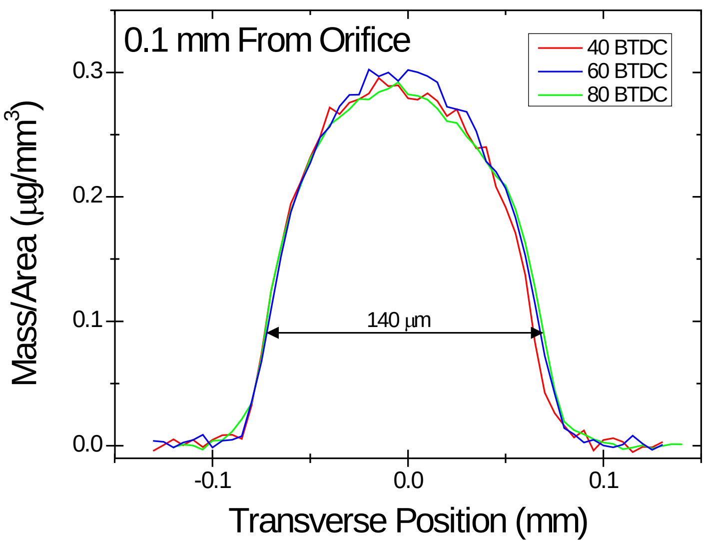


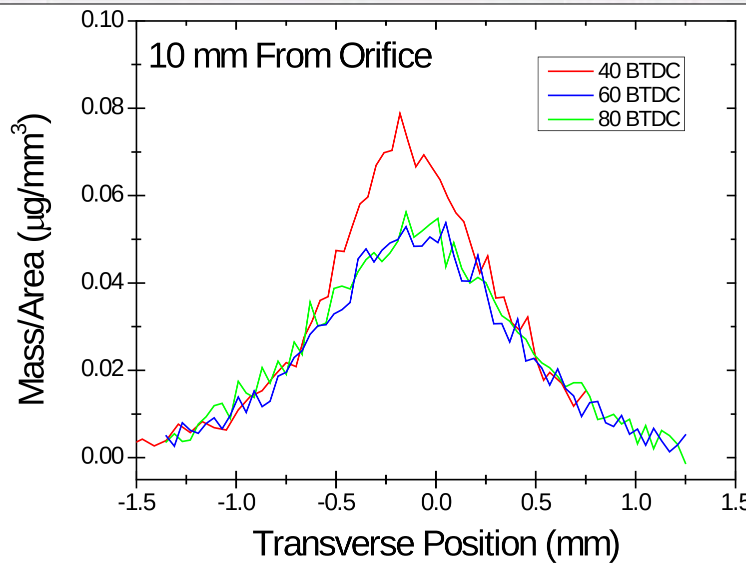


A similar heat release trend is observed as in case-1, and the pressure trace shows reasonably good agreement.

Gasoline Injection at Three Engine Operating Points







Design of Experiments Study

Design of experiment (D.O.E) matrix

Exp No	EGR	Boost	Injection Pressure
1	(-)	(-)	(-)
2	(+)	(-)	(-)
3	(-)	(+)	(-)
4	(+)	(+)	(-)
5	(-)	(-)	(+)
6	(+)	(-)	(+)
7	(-)	(+)	(+)
8	(+)	(+)	(+)

*Yates Algorithm was used

George E.P Box, William G Hunter and J. Stuart Hunter, Statistics For Experimenters- An Introduction to Design, Data Analysis and Model Building, John Wiley & Sons, Inc, USA.

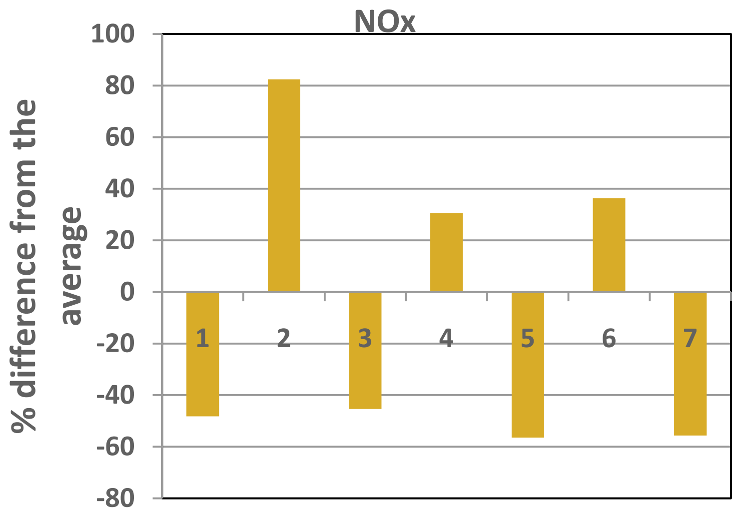
D.O.E matrix parameter values at 8 bar BMEP

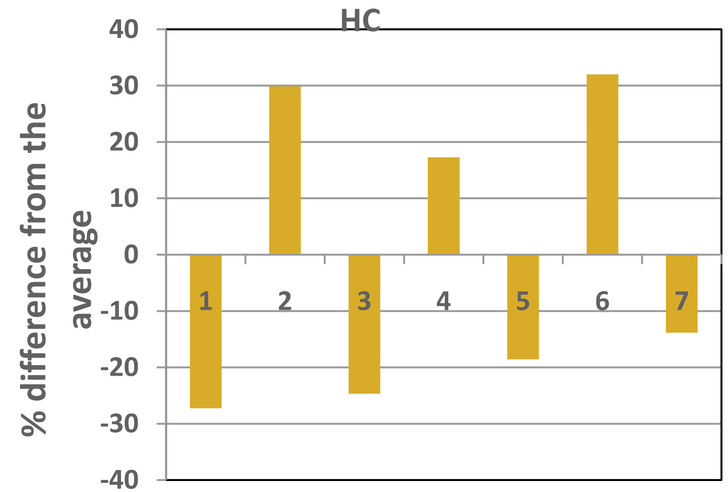
	EGR (%)	Boost (bar)	Injection Pressure (bar)
(+)	21	0.7	1000
(-)	13	0.5	500

Average values from DOE analysis at a BMEP of 8 bar

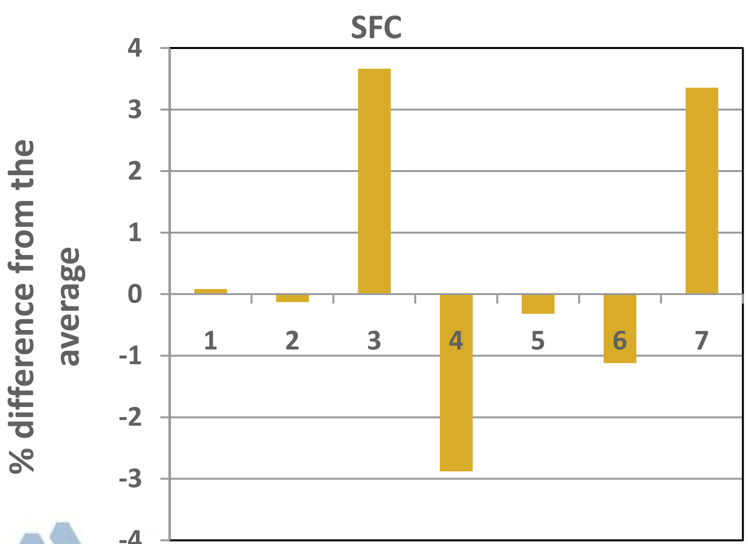
NOx g/kW-hr	HC g/kW-hr	CO g/kW-hr	SFC g/kW/hr	Noise db	COV of IMEP
1.51	1.26	5.36	238.7	93.5	1.3

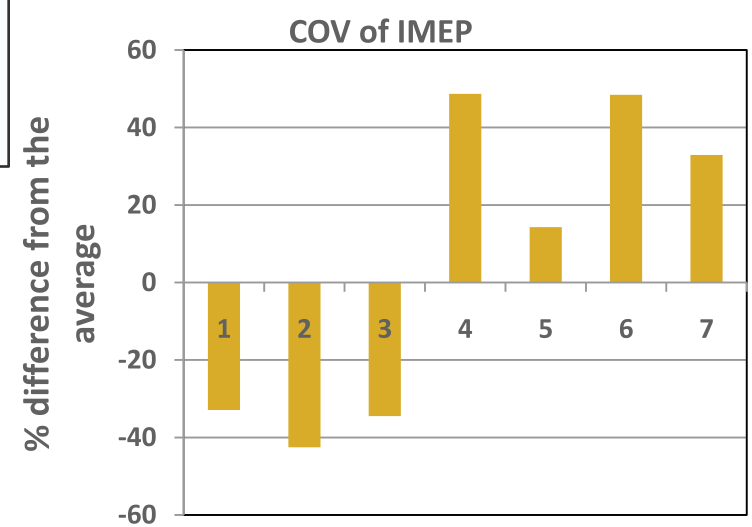
DoE Study @ 2500 RPM – 8 bar BMEP; EGR, P_inj and Boost as controls





- 1 - EGR
- 2-Boost
- 3-EGR&Boost
- 4- Inj. Pressure
- 5-EGR & Inj. Pressure
- 6-Boost & Inj. Pressure
- 7-EGR,Boost&Inj.Pre





Future Work

- Perform injection timing, EGR and # of injections sweep for the 4 test points
- Validate engine operation on lower cetane gasoline fuel
  - FACE fuel (~30 cetane)
- When LTC operation is determined, use combustion imaging to obtain detailed fluid mechanics and chemistry information
  - Spectroscopic measurements
  - Any possible soot radiation
- Continue to correlate results with APS spray data and with SNL's fundamental combustion work
  - We are all using identical hardware (Bosch Gen II)
  - Make data available to Engine Combustion Network (managed by SNL; Lyle Pickett)
- Perform tests using different injection inclusion angle to facilitate early injection timing for LTC.
- Validate test matrix using lower compression ratio pistons to achieve NO_x reduction with less EGR
- Make data available to vehicle powertrain simulations – data provided to Aymeric Rousseau for Autonomie simulation

Summary

- Power density versus Emissions and Efficiency issues are addressed in low cetane Gasoline LTC operation
- Combustion phasing and start of ignition control was dictated by fluid mechanics (Injection timings, Injection pressure and number of injections) with favorable chemistry behavior (EGR – intake air enthalpy/composition and Boost pressure-Oxygen concentration)
- Project has already demonstrated that 85 RON Gasoline fuel is promising in LTC by utilizing injection parameters for combustion phasing
- 80-85 RON fuels are of interest - by USCAR Tech Team
- New EGR valve setup mitigates the poor EGR distribution from cylinder to cylinder from the stock configuration
- Combustion imaging is a very familiar and well-validated tool to help us understand the characteristics of LTC
  - Will be simultaneously with pressure transducers, current clamps, emissions bench, fast FID and fast NO_x analyzers
- Working with GM and UW-Madison facilitates development of an approach for gasoline LTC operation.