Use of Low Cetane Fuel to Enable Low Temperature Combustion

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May 15, 2012

Project ID# ACE11

Overview

Timeline

- Started May 2008

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY11 $670k
  - FY12 $670k

Barriers

- From MYPP
  - Mechanism to control LTC Timing
  - LTC high load and high speed operation
  - LTC control during change of speed and load

Partners

- Argonne is project lead
- Partners are
  - GM Europe and GM R&D
    - 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
    - Controller algorithm upgrades

Objectives of this Study (Relevance)

- Focus upon gasoline-like (low cetane) fuels
  - A significant portion of Fuel/(Air+EGR) will be premixed, but not well mixed – some stratification will enable higher load operation and control of combustion phasing
  - Control "ignition propensity" through the use of fuel delivery, intake oxygen concentration (EGR), intake air temperature
- Maintain relatively high power densities (~20 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
- Correlate ignition information with collaborators at UW-ERC, GM, Argonne and the AEC partners.

Milestones

Milestone	Target Date
Injection and EGR sweeps for 4 operating points • Sensitivity study for these inputs • Compare injection strategy and EGR levels	Aug 2011 (Complete)
Operate the engine at high load (~20 bar BMEP)	Dec 2011 (Complete)
Use uncooled EGR to enable low load/speed operation	Feb 2012 (Complete)
Validate additional engine operating conditions with Autonomie • Peak Efficiency • Lowest NO_x	Apr 2012 (Ongoing)
Switch to 70 RON FACE Fuel	FY13
Endoscope Imaging	FY13
VVA, GDI, Advanced Turbo-charging capability	FY14

Approach

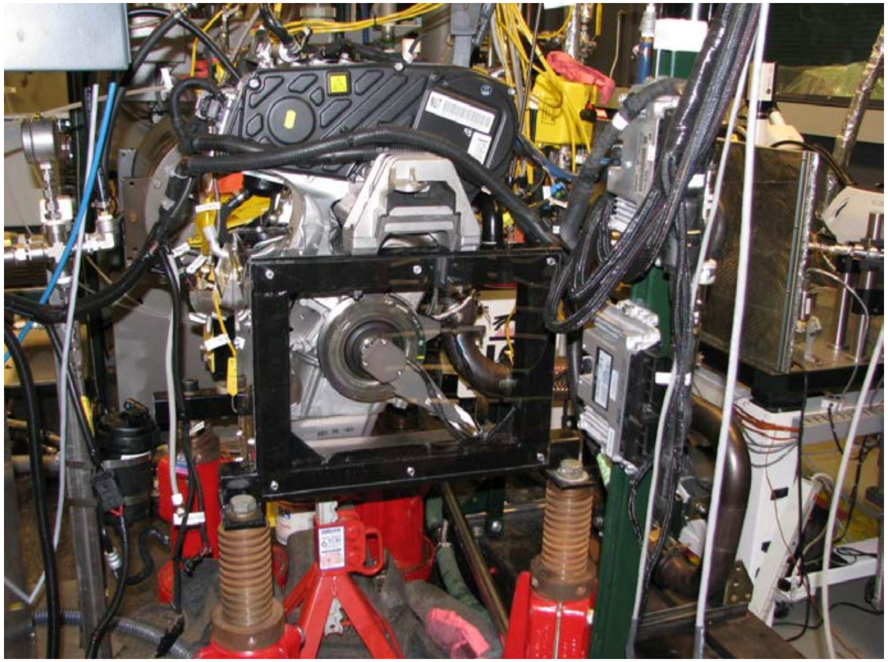
- This project will use low cetane/high volatility fuel
  - Significantly increase ignition delay
  - Limit/eliminate wall and piston fuel wetting
    - Use 500 bar injection pressure
  - Use recent gasoline FACE fuel developments
- Gasoline-like fuels with low cetane/high volatility
- Engine conditions provided by Autonomie simulation for maximum relevance to automobile simulation predictions
- Use fluid mechanics (injection parameters) and EGR 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
- Leverage Argonne Rapid Compression Machine work to better understand ignition parameters.

Engine Specifications and Tested Fuels Properties

Engine Specifications

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

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



Experimental Setup

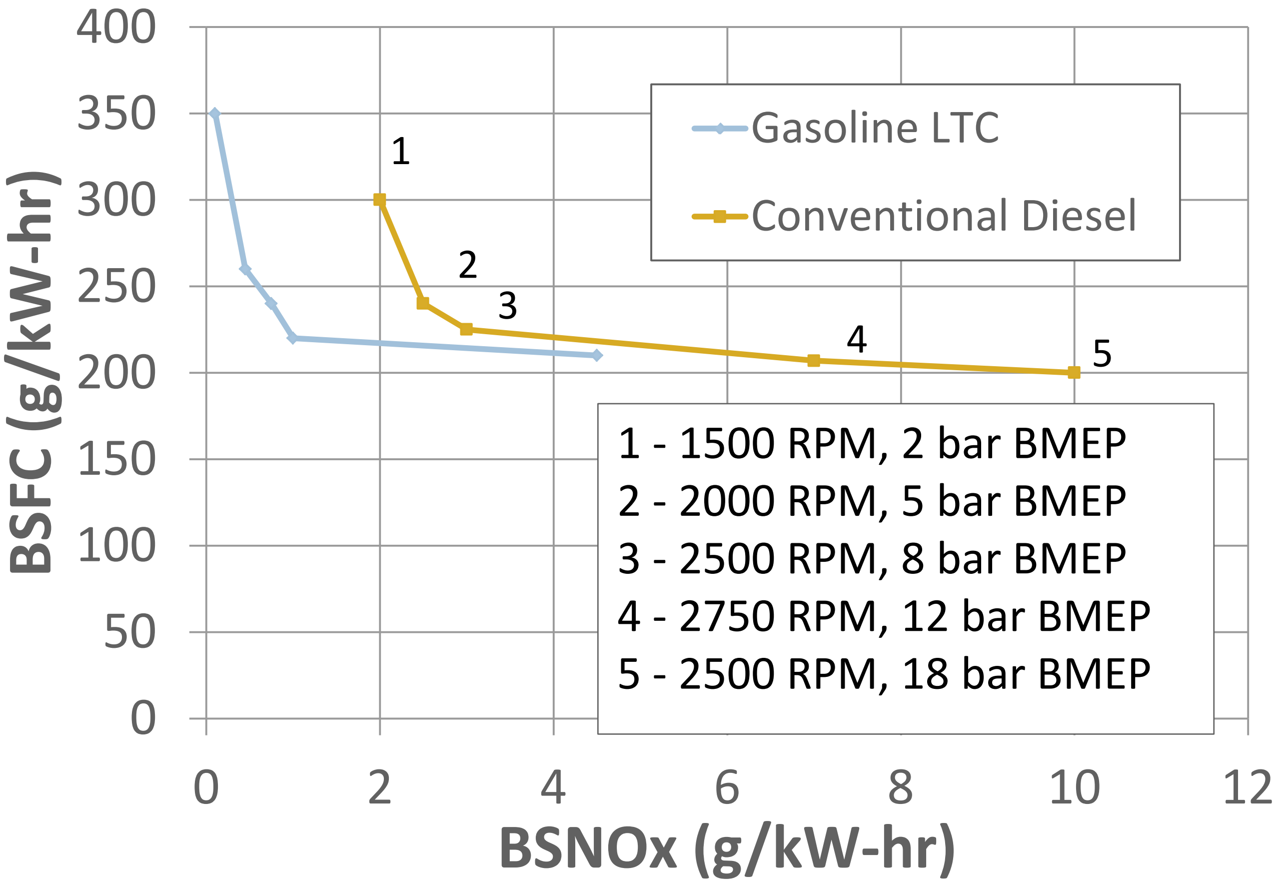
Properties of the Two Tested Fuels

Property	#2 diesel	Low-octane 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

Technical Accomplishments

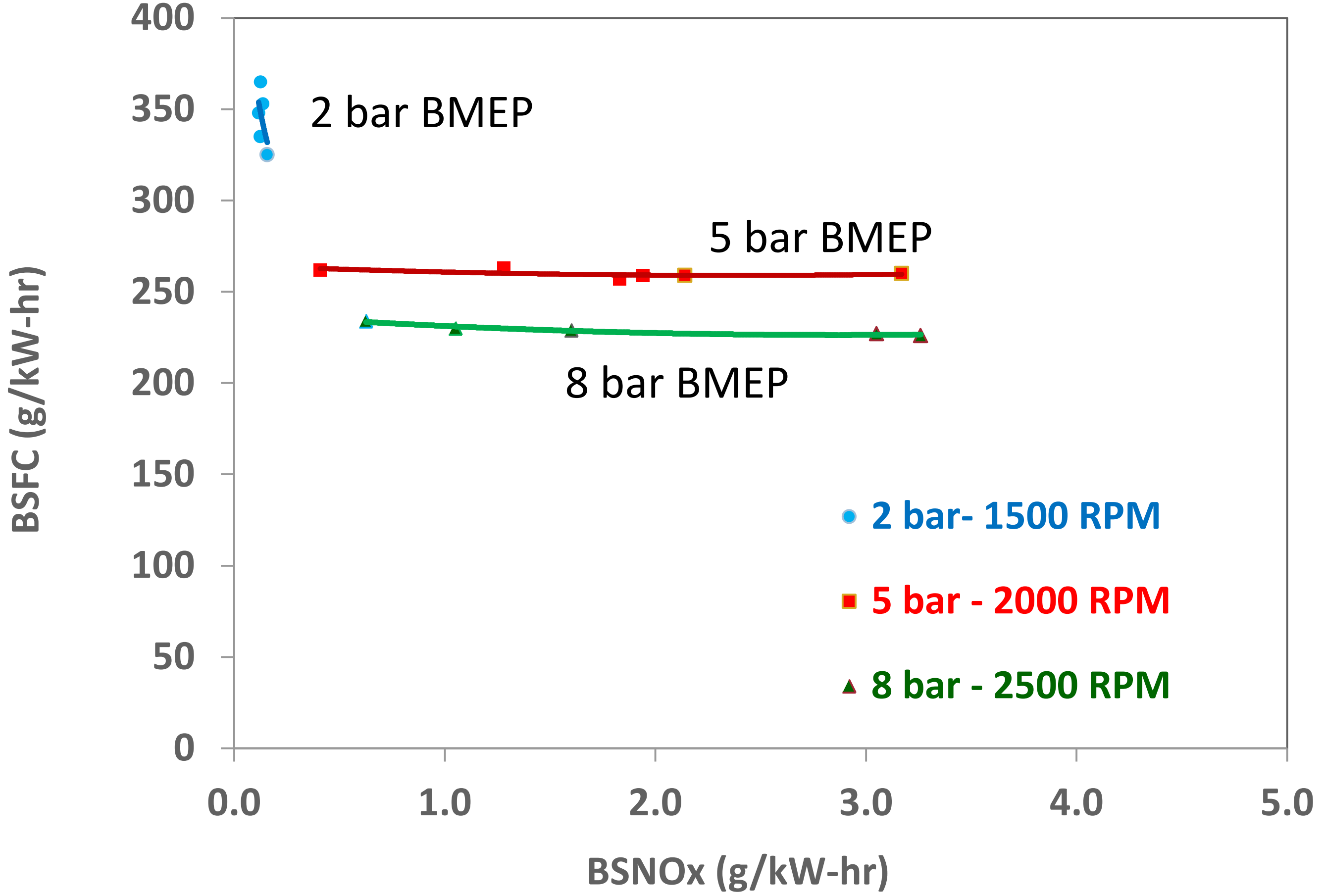
- Successfully operated the engine using low cetane fuels
  - Instructed to focus upon 87 RON fuel by USCAR tech team
- Low NO_x emissions levels achieved – typically below 1 g/kW-hr
- 4 GM provided target engine operating conditions
  - 2 bar BMEP at 1500 RPM
  - 5 bar BMEP at 2000 RPM
  - 8 bar BMEP at 2500 RPM
  - 12 bar BMEP at 2750 RPM
- Have successfully operated engine at 20 bar BMEP at 2500 RPM.
- Successfully achieved 33 - 40% BTE for 3 of the 4 GM points
- Successfully incorporated uncooled EGR to assist in ignition propensity at low speed/load conditions
  - Increased T_intake allowed for standard triple injection strategy
- All operating points produce below 0.2 FSN – most below 0.1 FSN

BSFC vs. BSNO$_x$ for Gasoline LTC compares favorably to Conventional Diesel



Significantly reduced PM and NO$_x$ for similar BSFC

Effect of EGR rates in BSFC and BSNOx in LTC



EGR trends are opposite to diesel – CO and HC emissions tend to decrease and combustion efficiency increases as EGR increases

EGR Sweep Efficiency Values (2 bar, 5 bar, 8 bar BMEP)

2 bar BMEP, 1500 rpm

% EGR	η Combustion	η Thermodynamic	η Gas Exchange	η Mechanical	η Total
29	0.917	0.365	0.959	0.748	0.240
20	0.906	0.340	0.952	0.785	0.230
12	0.917	0.368	0.956	0.773	0.249
5	0.906	0.357	0.952	0.770	0.237
0	0.925	0.379	0.956	0.767	0.257

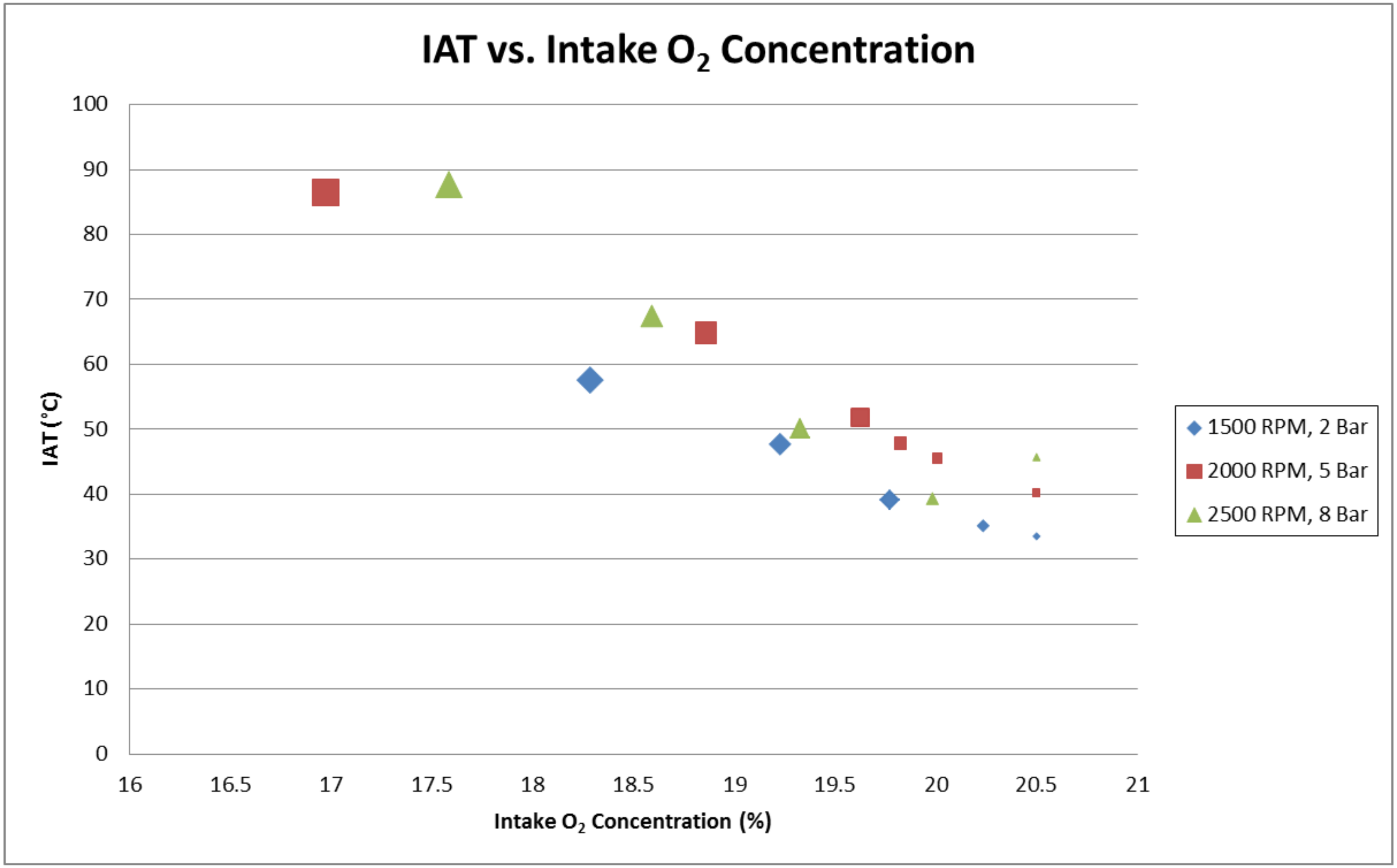
5 bar BMEP, 2000 rpm

% EGR	η Combustion	η Thermodynamic	η Gas Exchange	η Mechanical	η Total
27	0.987	0.423	0.916	0.820	0.313
17	0.980	0.430	0.933	0.801	0.315
10	0.976	0.428	0.944	0.815	0.321
8	0.976	0.429	0.941	0.812	0.320
6	0.975	0.425	0.941	0.820	0.319
0	0.970	0.421	0.943	0.828	0.319

8 bar BMEP, 2500 rpm

% EGR	η Combustion	η Thermodynamic	η Gas Exchange	η Mechanical	η Total
20	0.992	0.423	0.964	0.876	0.354
15	0.990	0.432	0.963	0.876	0.360
10	0.986	0.437	0.963	0.874	0.363
5	0.982	0.458	0.957	0.854	0.368
0	0.984	0.442	0.957	0.878	0.366

Intake Air Temperature (IAT) vs. Intake O_2 Concentration

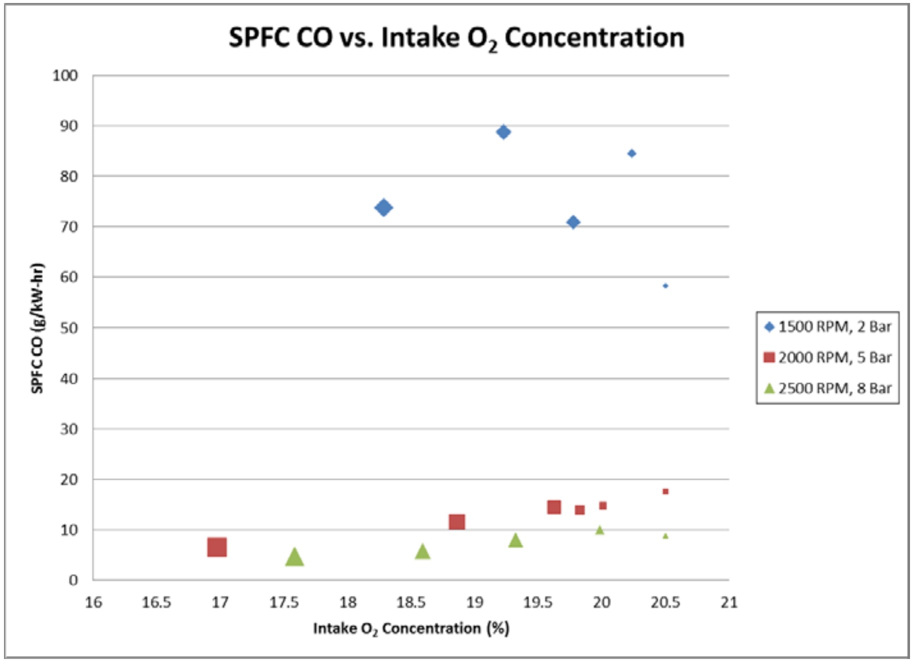


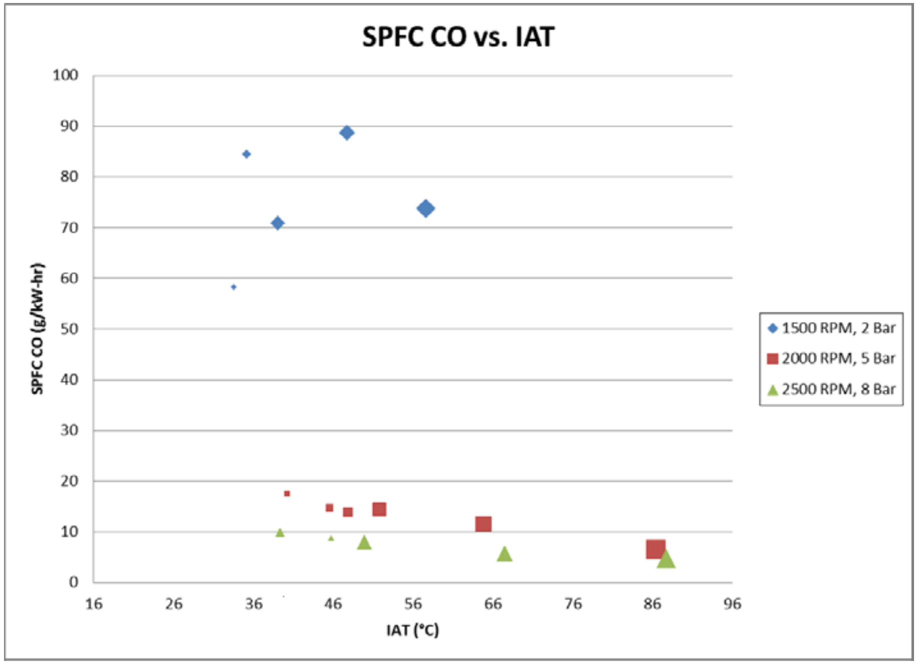
Increased IAT trends with increased EGR

Note: Increasing marker size corresponds to increasing EGR Rate. For example:

🟥 = max EGR ▪ = min EGR

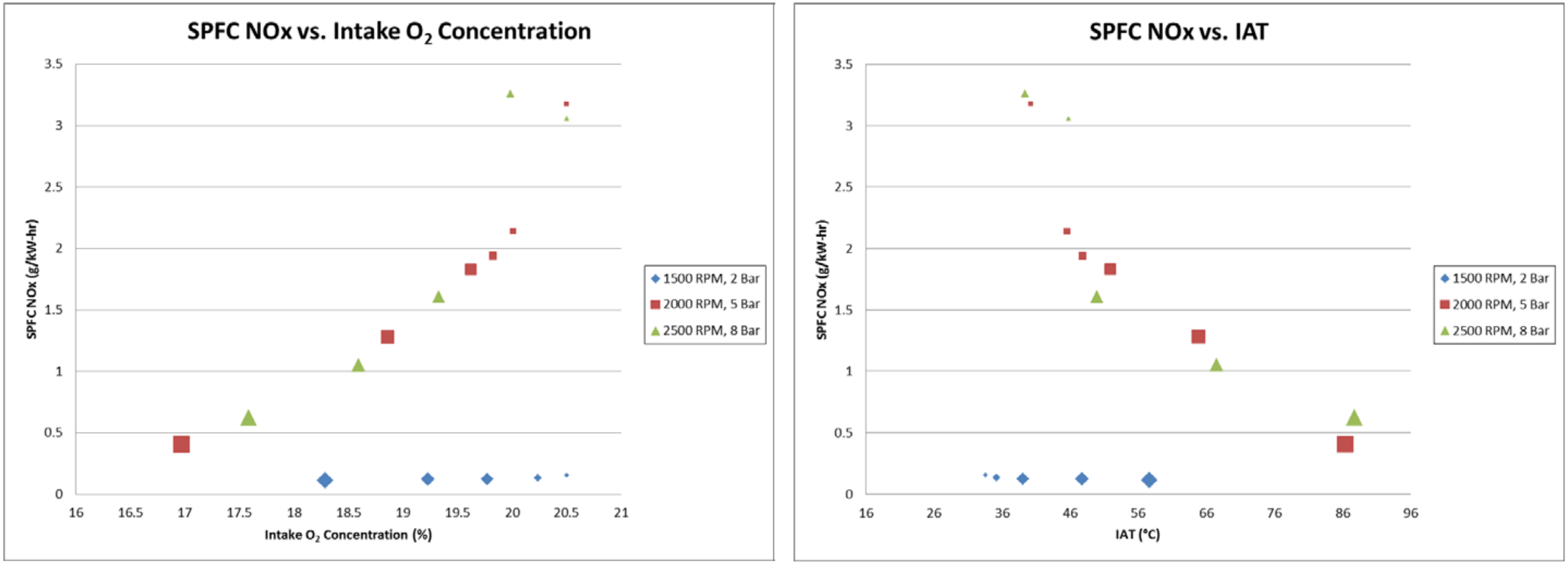
SPFC CO vs. Intake O_2 Concentration and IAT



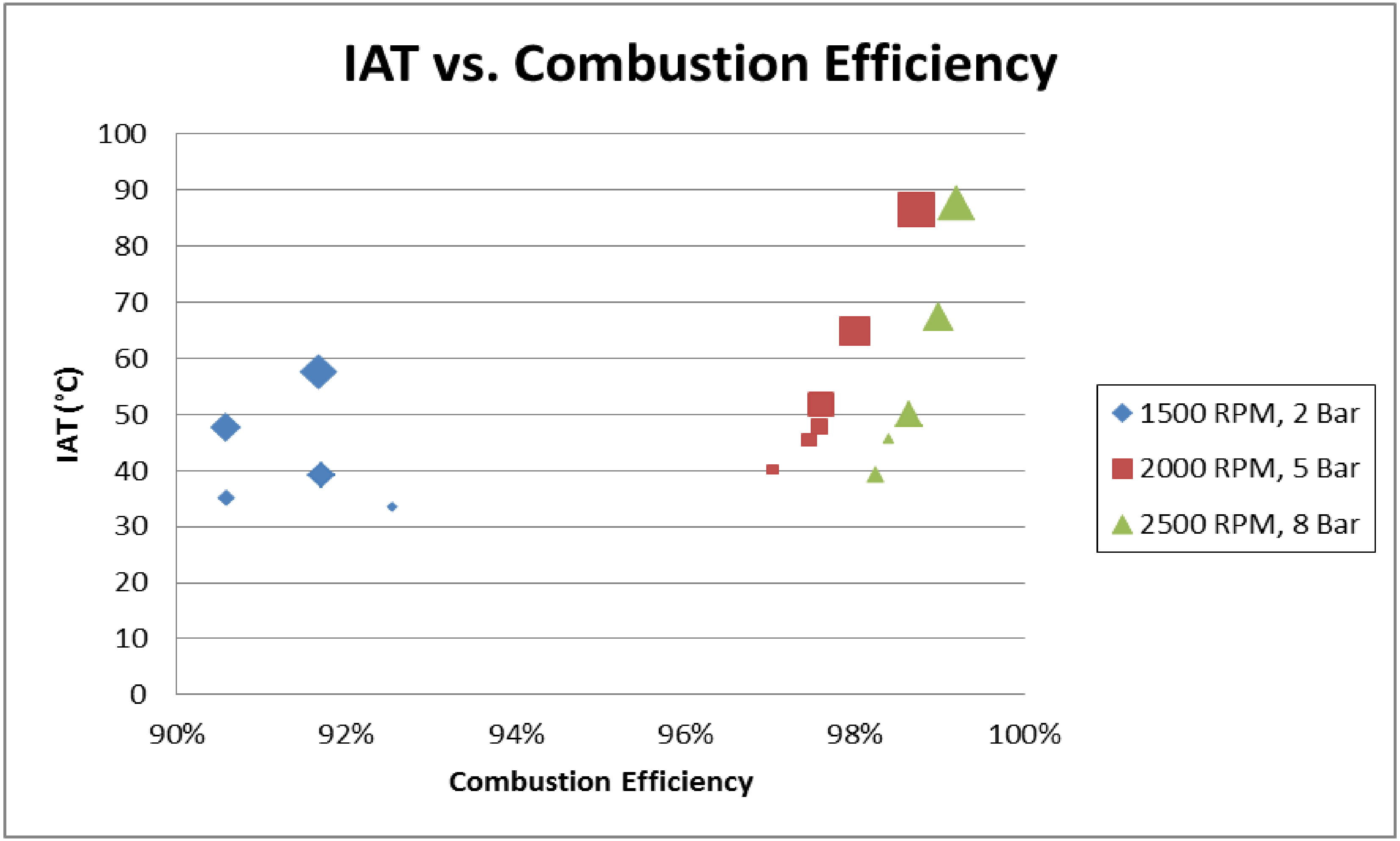


CO emissions are more dependent on IAT than intake oxygen concentration, as opposed to traditional diesel operation

SPFC NO_x vs. Intake O_2 Concentration and IAT



Intake oxygen concentration drives NO_x production similar to traditional diesel operation while IAT shows the opposite trend

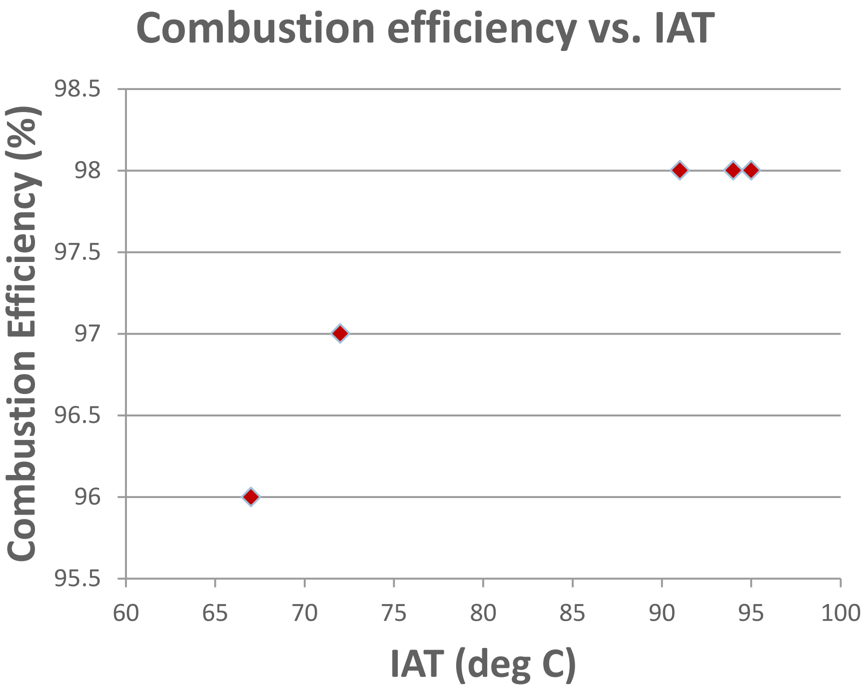


Higher IAT through increased EGR showed improvements in combustion efficiency with the exception of low load – more reliable ignition

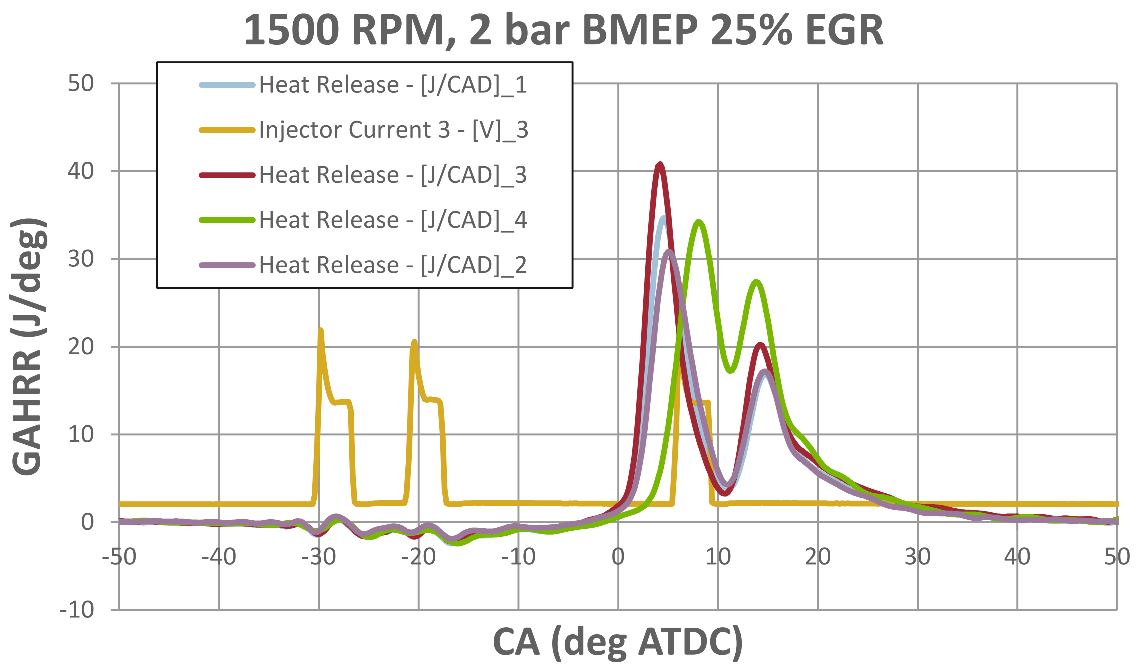
Cases Shown:
2 bar, 1500 RPM: 0%, 5%, 12%, 20%, 29% EGR
5 bar, 2000 RPM: 0%, 6%, 8%, 10%, 17%, 27% EGR
8 bar, 2500 RPM: 0%, 5%, 10%, 15%, 20% EGR

2 bar BMEP at 1500 RPM is difficult to optimize - perhaps a new strategy?

- Uncooled EGR was incorporated to increase ignition propensity at low load/speed conditions
- Increase in IAT should outweigh small decrease in Intake O_2 concentration
- Increase in IAT also allowed for use of standard triple injection strategy instead of quasi-HCCI early single injection
- All data is for 2 bar BMEP at 1500 RPM
- EGR increased from 15% to 25% for the increased IAT



New approach using uncooled EGR for low load/speed results in improved performance

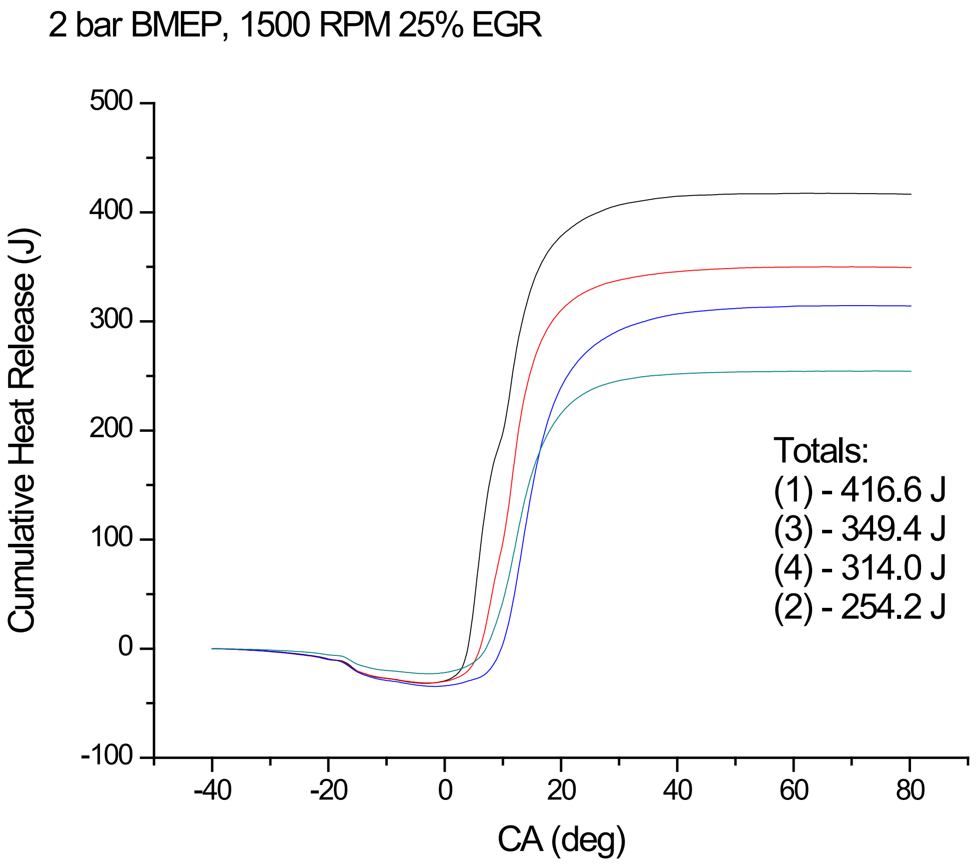


BSFC (g/kW-hr)	**BSNO$_x$ (g/kW-hr)**	**BSCO (g/kW-hr)**	**BSHC (g/kW-hr)**	**Noise (dB)**
345	0.52	6.7	6.3	80

(CO and HC are an order of magnitude lower than previous approach)

Low load/speed operation indicates more room for improvement

- Inconsistent fueling at low loads appears to be occurring
  - Integrated fuel consumption from HR curves display this characteristic
  - Incorporating injector trim should address this issue



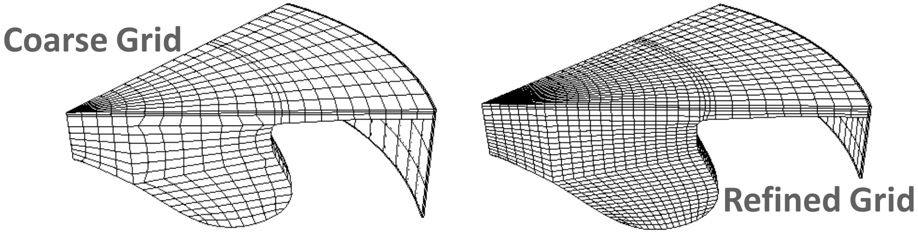
KIVA Simulations from UW-Madison ERC

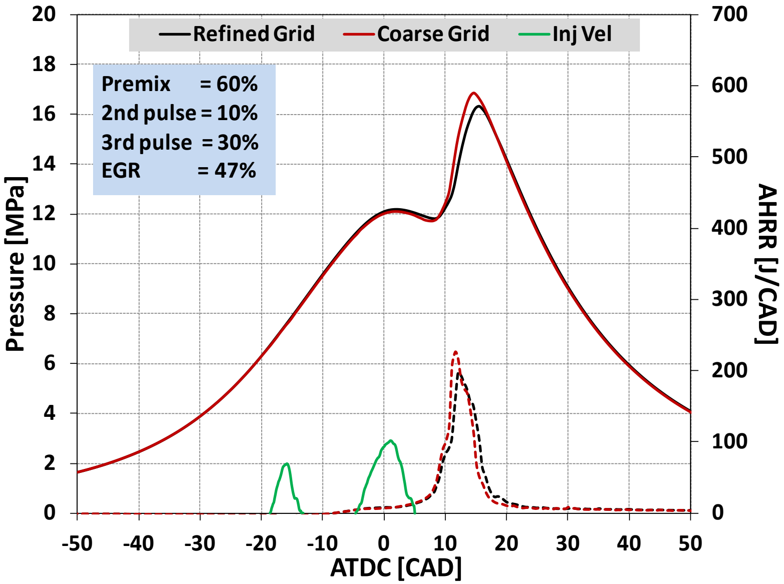
Modeling Parameters from UW-ERC

GM 1.9L Single Cylinder Engine; CR=16.5	
IVC Pressure [bar]	3.25
IVC Temperature [K]	361
Total Fuel Amount [mg/cyc]	43.6
Engine RPM	2500
Injection Pressure [bar]	1160
Premixed Fuel Fraction	0.6
Fuel Fraction in 2nd Pulse	0.1
Start of 2nd Pulse [ATDC]	-18.6
Start of 3rd Pulse [ATDC]	-4.6
%EGR	47

	Coarse	**Refined**
Cells at IVC	~10500	~32600
Average Cell Size [mm]	~1.6	~0.6

Emission Results	**Coarse**	**Refined**
Soot @ EVO [g/kW-hr]	0.045	0.040
NOx @ EVO [g/kW-hr]	0.017	0.028
CO @ EVO [g/kW-hr]	37.086	38.159
UHC @ EVO [g/kW-hr]	10.817	10.323

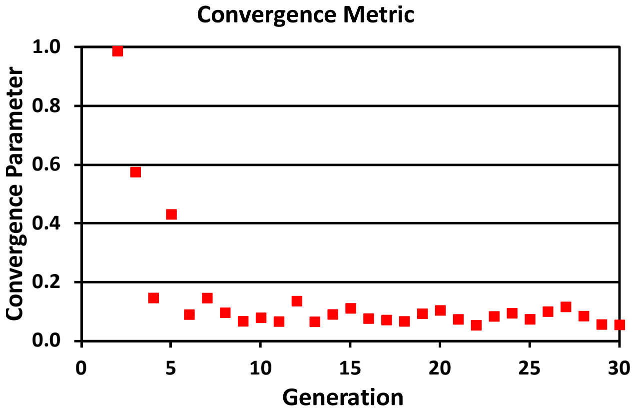




- **Coarse and refined grid results are in reasonable agreement.**
- **To save computational time, coarse grid was used for the optimization study.**

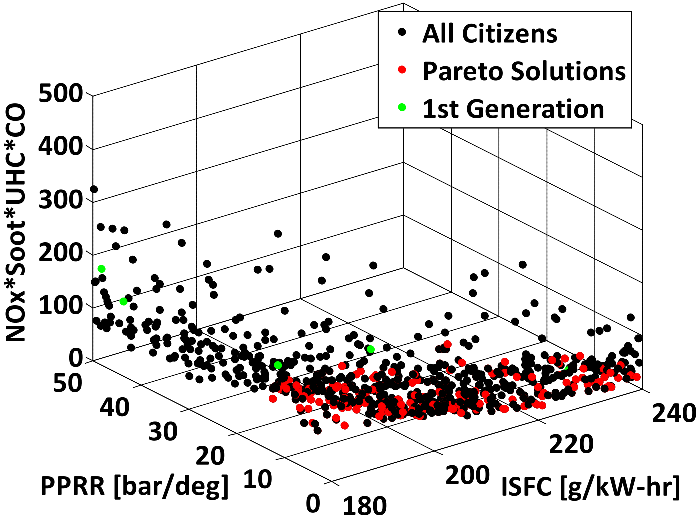
Engine Optimization Parameters

GA Optimization Parameters	
Boost Pressure [bar]	2 to 5
Premixed Fuel Fraction	0 to 1
Ratio of fuel fraction in 2nd & 3rd pulse	0 to 1
Start of 2nd Pulse [ATDC]	-80 to +30
Start of 3rd Pulse [ATDC]	-80 to +30
%EGR	10 to 55



Pareto front advancement stopped after ~15th generation.
Simulations were performed until 30th generation to confirm the convergence.

Objective was to minimize NO_x, soot, CO, UHC, ISFC and PPRR.



It can be noticed that there are not many pareto solutions at the center of this chart, which indicates that at this high load it is difficult to maintain a low value of both ISFC and PPRR at the same time.

Optimal Designs

	Baseline	**Design-1**	**Design-2**
Generation	-	7	14
Citizen	-	0	12
IVC Pressure [bar]	3.25	3.25	3.29
Premixed Fuel %	60.0	60.0	40.8
Fuel % in 2nd Pulse	10	9.6	48.8
Fuel % in 3rd Pulse	30	30.4	10.6
Start of 2nd Pulse [ATDC]	-18.60°	-76.09°	6.31°
Start of 3rd Pulse [ATDC]	-4.6°	-4.6°	10.0°
%EGR	47.0	47.0	30.8
Performance Analysis			
ISFC [g/kW-hr]	204.55	198.83	213.91
NOx [g/kW-hr]	0.017	0.019	0.437
Soot [g/kW-hr]	0.045	0.027	0.065
CO [g/kW-hr]	37.09	29.55	14.50
UHC [g/kW-hr]	10.82	8.97	9.04
PPRR [bar/deg]	15.84	18.18	7.03
Ringing Intensity [MW/m^2]	28.51	35.78	6.79
IVC to EVO Thermal Eff [%]	40.57	41.94	39.00

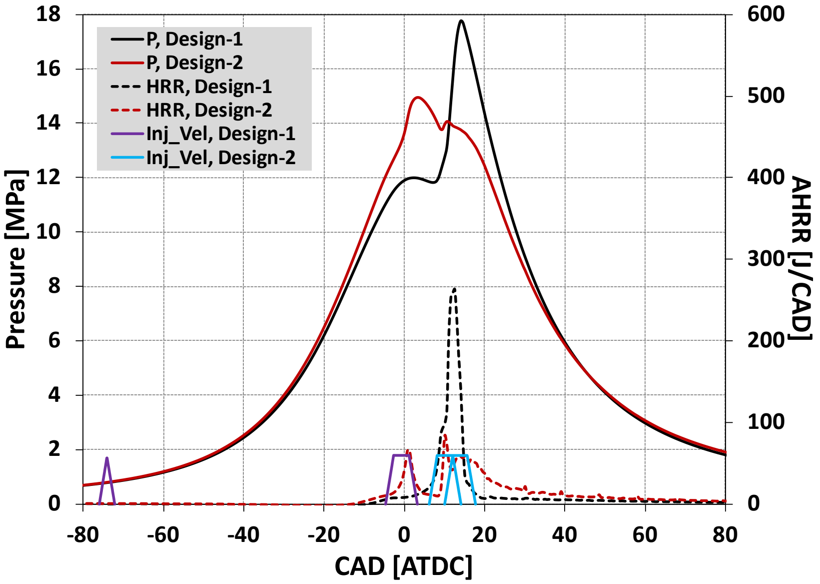
Large amount of premixing in *Design-1* results in a very high PPRR.

***Design-2* indicates a two-stage combustion behavior.**

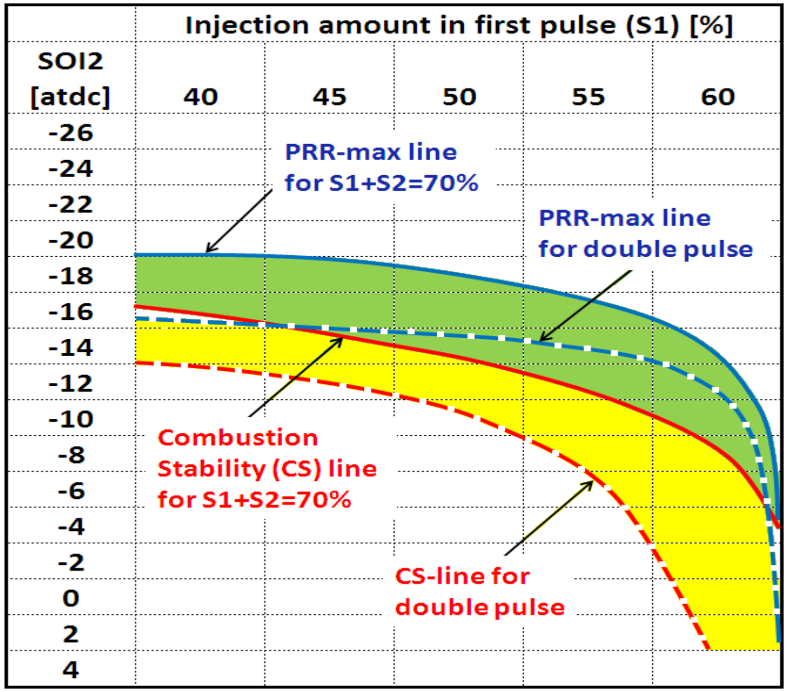
***Design-1:* Triple Pulse; High EGR [47%]**

***Design-2:* Double Pulse; Relatively Low EGR [30.8%]**

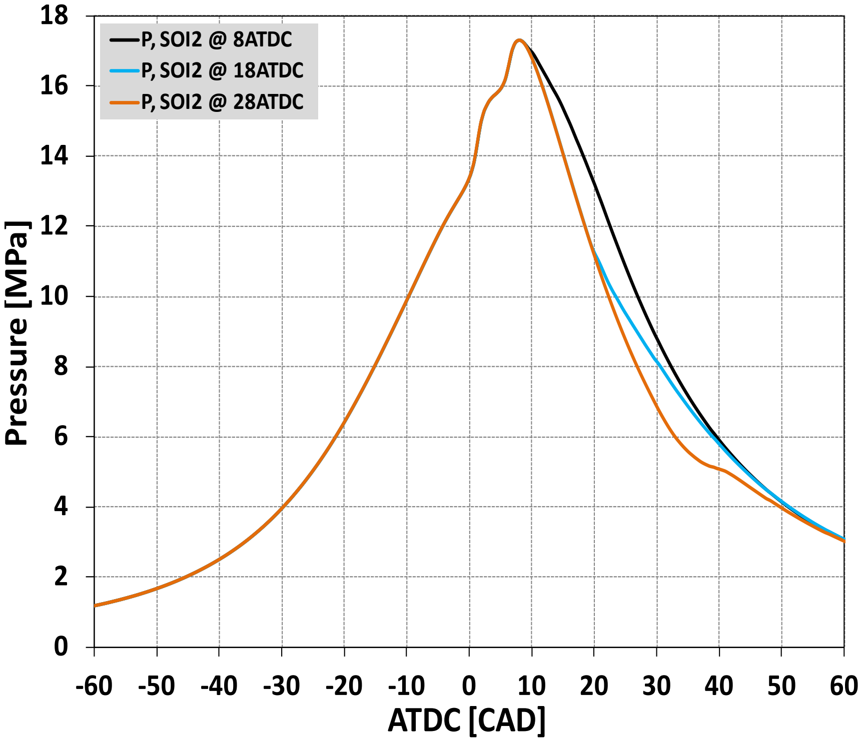
***Design-1* is comparable to the *Baseline* case.**



Engine Operation Map



High EGR Regime [47% EGR]



- In high EGR regime, PPRR is controlled by the level of premixing and 2nd pulse fuel amount and timing.
- In low EGR regime, PPRR is restricted mainly by premixed fuel amount.
- Premixing amount in low EGR regime is restrained by the lower EGR usage.
- Low EGR map shows a wide operating regime at 50% premixing.
- *Intake Temperatures are assumed to be roughly 40 C – EGR cooling at high load required!*

Future Work (near term)

- Reduced injection pressure of 500 bar will also be attempted
  - Previous injection pressure has been 1000 bar for all cases
  - Reduced injection pressure should assist in HC and CO emissions at low speed/load
- Close-linked Double pilot injection with a 500 µs dwell to the main injection
  - Recommended by GMPTE engineer
- Depending upon results of these strategies, next step may include the use of the reduced inclusion angle injector tip to decrease the HC and CO emissions
- Working with Drivven to develop injector trim approach for more consistent cyl-to-cyl fueling at low load operation
  - Should improve COV and cyl-to-cyl consistency

Future Work (medium term)

- Finish the additional points required using 87 RON gasoline to complete required Autonomie vehicle simulation.
  - Points will be operated twice; EGR related
    - Peak efficiency
    - Best NOx emissions
- Low load conditions are likely to provide ignition challenges
  - Collaborate with Argonne RCM project for auto-ignition information
    - Gasoline surrogates, following Westbrook's 5 component approach
  - Use endoscope imaging to identify ignition locations and timings
  - Use simulation to guide optimization possibilities
- Switch Fuels to 70 RON FACE fuel
  - Run the 10 point test matrix again with 70 RON fuel
  - Compare the operation of the two fuels and the influence upon simulation vehicle fuel economy

Summary

- 4 GM suggested operating conditions have been characterized
  - 1500 RPM, 2 bar BMEP
  - 2000 RPM, 5 bar BMEP
  - 2500 RPM, 12 bar BMEP
  - 2750 RPM, 12 bar BMEP
- Significant data set acquired at these conditions, altering EGR, boost, injection pressure, etc.
  - This data already shared with GM and GMPTE
- The three higher load conditions produced diesel-level efficiencies with significantly reduced NOx and comparable HC and CO emissions to diesel
- Other higher load operating conditions have also been explored – up to 18 bar BMEP at 2500 RPM
- The 1500 RPM, 2 bar BMEP case is a challenge with current engine hardware and fuel.
  - Uncooled EGR was effective in improving ignition quality
  - Addition of advanced injector trim capability should improve performance

Technical Back up slides

Efficiency Equations

$$\eta_{Combustion} = 1 - \frac{\dot{m}_{CO} * Q_{LHV,CO} + \dot{m}_{HC} * Q_{LHV,HC}}{\dot{m}_{fuel} * Q_{LHV,fuel}}$$

$$\eta_{Thermodynamic} = \frac{(GIMEP) * \left(V_{d_{one\ cyl}}\right) * (N)}{\eta_{comb} * (Q_{LHV}) * (\dot{m}_f) * 2}$$

$$\eta_{Gas\ Exchange} = \frac{IMEP_{Net}}{IMEP_{Gross}}$$

$$\eta_{Mechanical} = \frac{BMEP}{IMEP_{Net}}$$

$$\eta_{Total} = \eta_{Combustion} * \eta_{Thermodynamic} * \eta_{Gas\ Exchange} * \eta_{Mechanical}$$