Use of Low Cetane Fuel to Enable Low Temperature Combustion

Stephen Ciatti

Argonne National Laboratory

May 14, 2013

Project ID# ACE11

Overview

Timeline

- Started May 2008

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY12 $670k
  - FY13 $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, and boost pressure
- 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, injection pressure, and 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
Install injector trim on all 4 cylinders	Jun 2012 (Complete)
Validate additional engine operating conditions with Autonomie • Peak Efficiency • Lowest NO_x	Sep 2012 (Complete) (Ongoing)
Test fuels with different octane ratings to study effect upon performance	Nov 2012 (Ongoing)
Use a cetane enhancer (Ethyl Hexyl Nitrate) to simulate different RON fuel	Dec 2012 (Ongoing)
Demonstrate wide range of engine load (2.5 bar – 19 bar BMEP) on 1 fuel (93 RON – 87 AKI)	Mar 2013 (Complete)

Approach

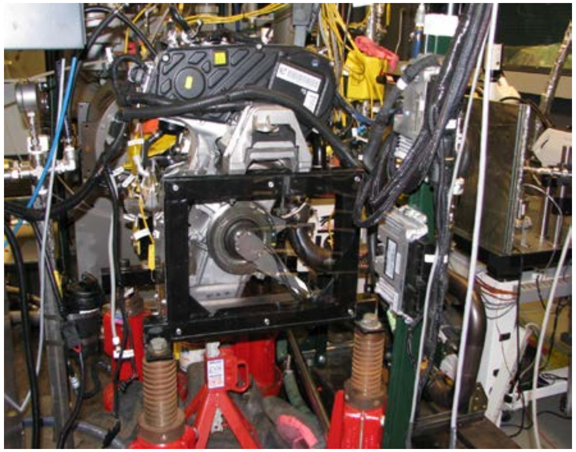
- This project will use low cetane/high volatility fuel
  - Significantly increase ignition delay
  - Limit/eliminate wall and piston fuel wetting
    - Use 500 bar injection pressure
    - Higher volatility fuels
- Gasoline-like fuels with low cetane/high volatility
- Engine conditions provided by Autonomie 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

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
Umbrella Angle	148 deg

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



Experimental Setup

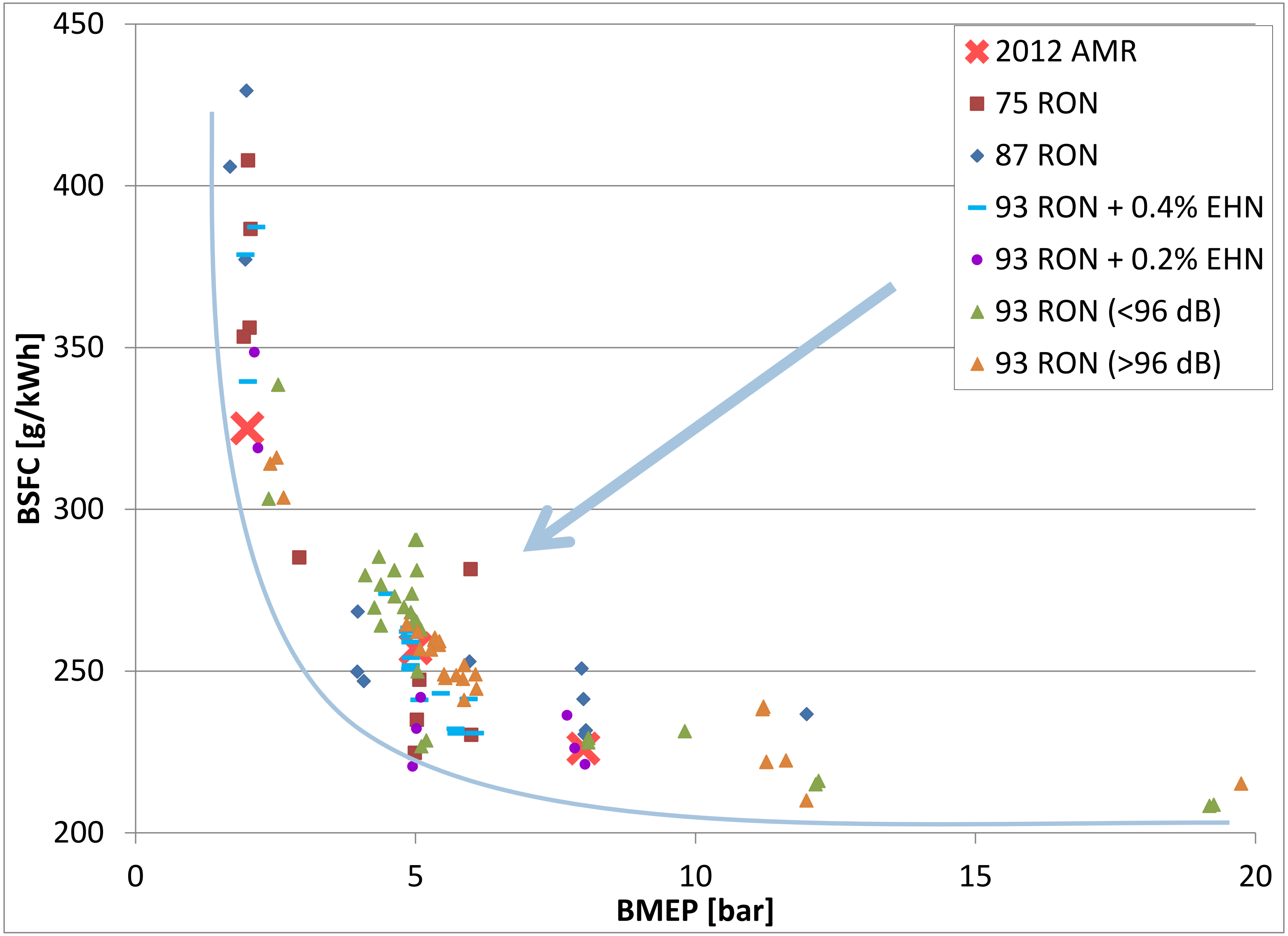
Properties of some of the Tested Fuels

Property	75 RON gasoline	87 RON gasoline	93 RON gasoline	93 RON + 0.2% EHN	93 RON + 0.4% EHN
Specific gravity	.6590	0.7512	.7018	.7018	.7018
Low heating value (MJ/kg)	45.2	43.5	44.0	44.0	44.0
Initial boiling point (°C)	81.7	86.8	93.2	93.2	93.2
T10 (°C)	98.0	137.8	119.8	119.8	119.8
T50 (°C)	120	197.8	148.8	148.8	148.8
T90 (°C)	162	225.1	234.2	234.2	234.2
Cetane Index	24.4	17.0	12.8	Est. 17	Est. 24

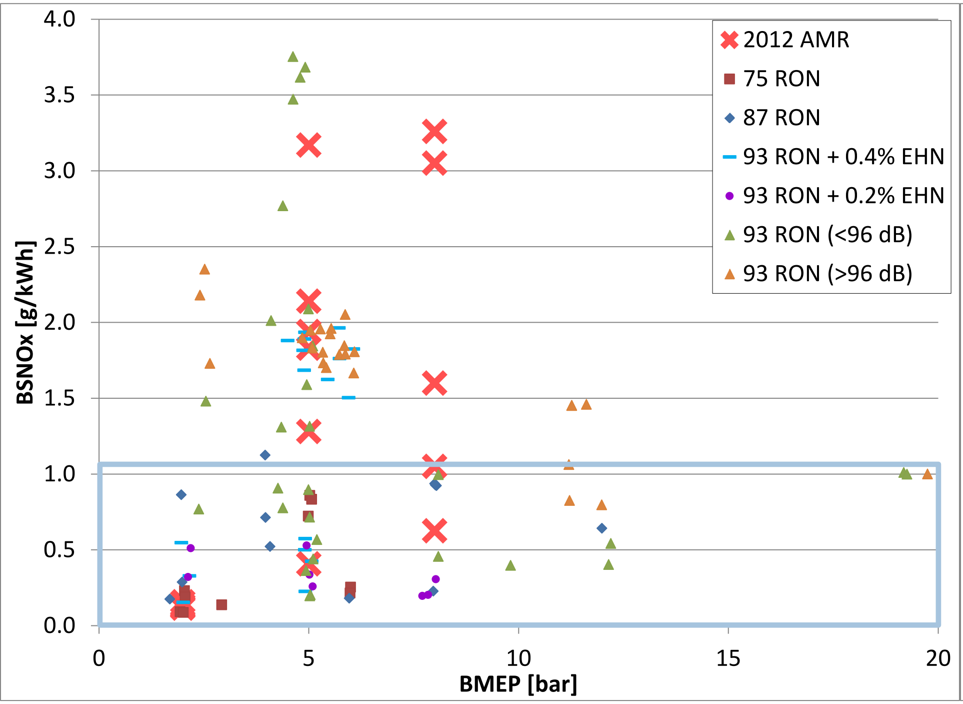
Technical Accomplishments

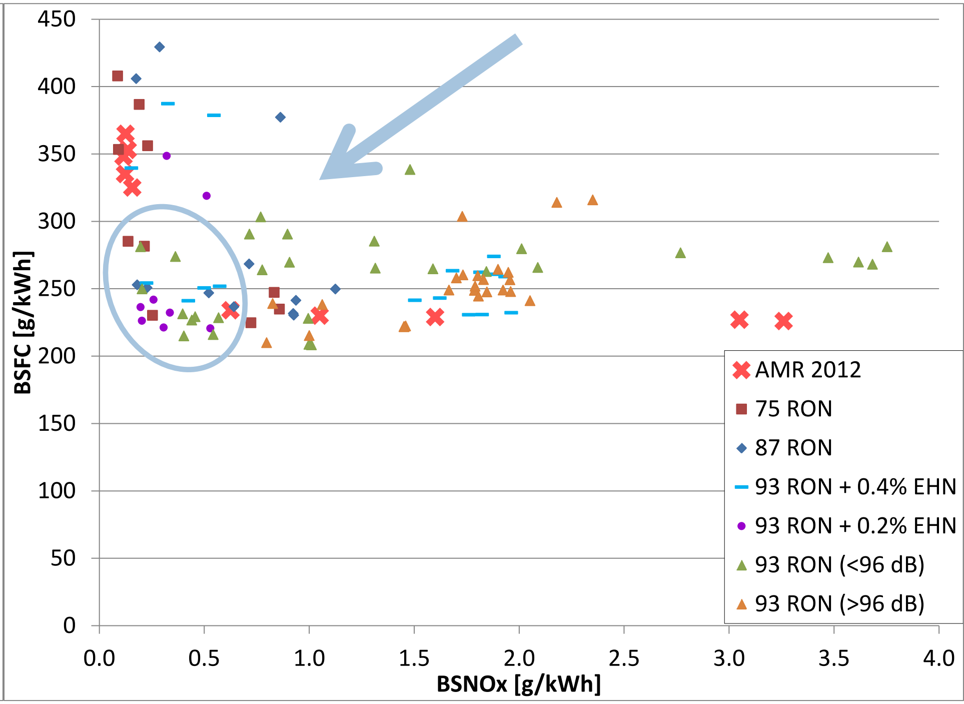
- Successfully operated the engine using a variety of low cetane fuels
  - RON varied from 75 to 93
- Low NO_x emissions levels achieved – typically below 1 g/kW-hr
- Demonstrated successful operation over a wide range of load using 93 RON gasoline (87 AKI)
  - 2.5 bar to 19 bar BMEP
- Added EHN to fuel and operated preliminary performance tests
  - Collaborative work with Argonne RCM and UW-ERC
- Provided 29 performance points to Autonomie simulation to evaluate fuel economy performance in a vehicle
  - 21% Fuel Economy improvement using LTC engine vs. PFI
  - 8% Fuel Economy improvement using LTC engine vs. DISI
  - Optimized efficiency points are still in progress for LTC engine
    - NO_x – BSFC tradeoff still to be completed

Operation of LTC with Fuels 75-93 RON



Low NO_x emissions achieved…

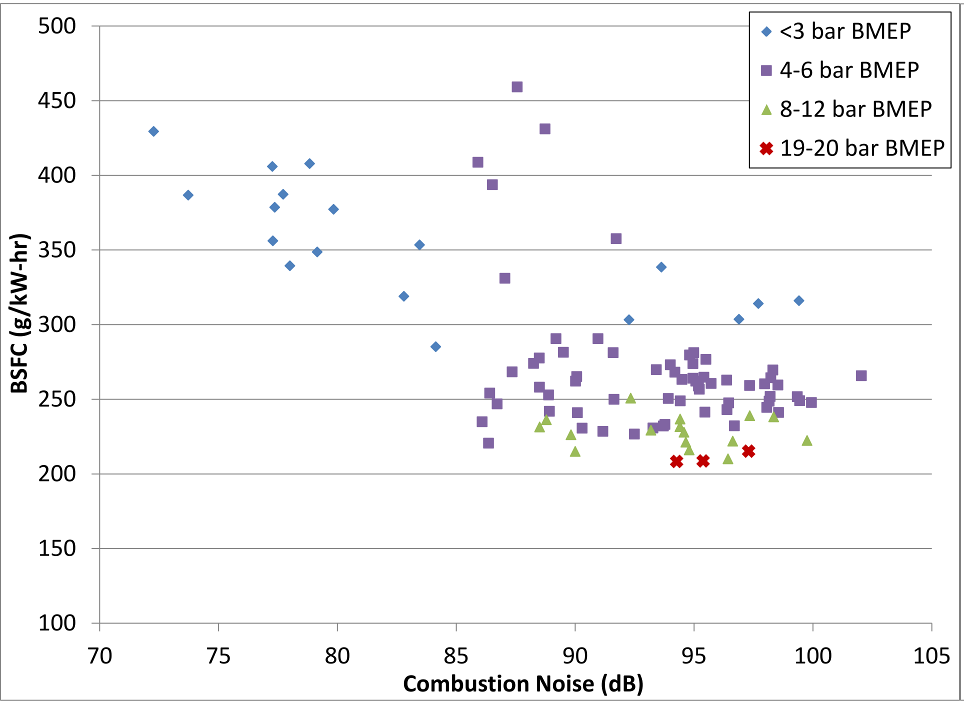


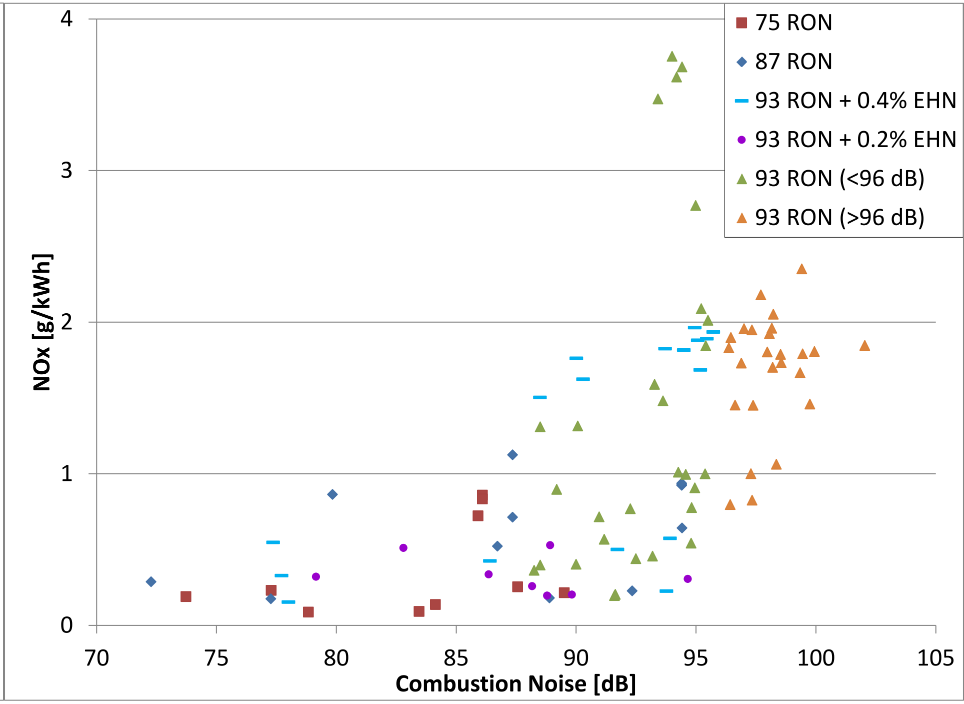


…across several engine loads.

…with simultaneously lower BSFC.

Combustion Noise Considerations

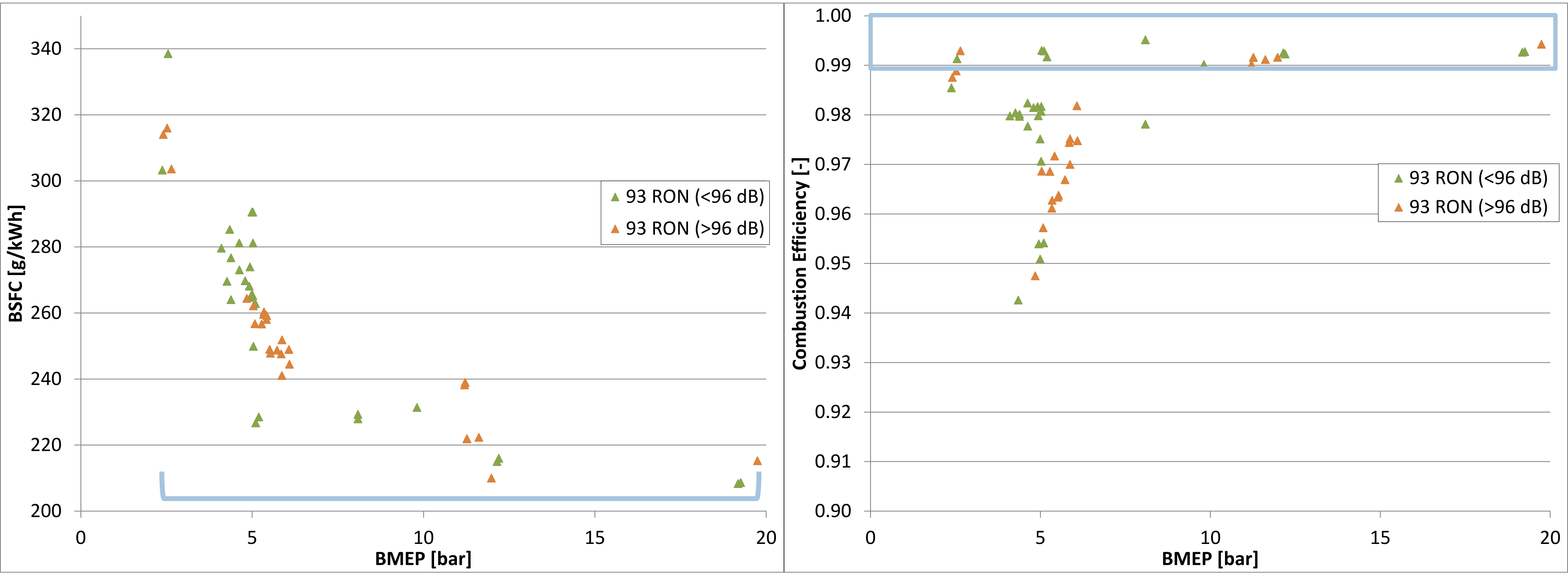




Per engine load, increased combustion noise corresponded with reduced BSFC.

But lower combustion noise corresponded with lower NO_x emissions.

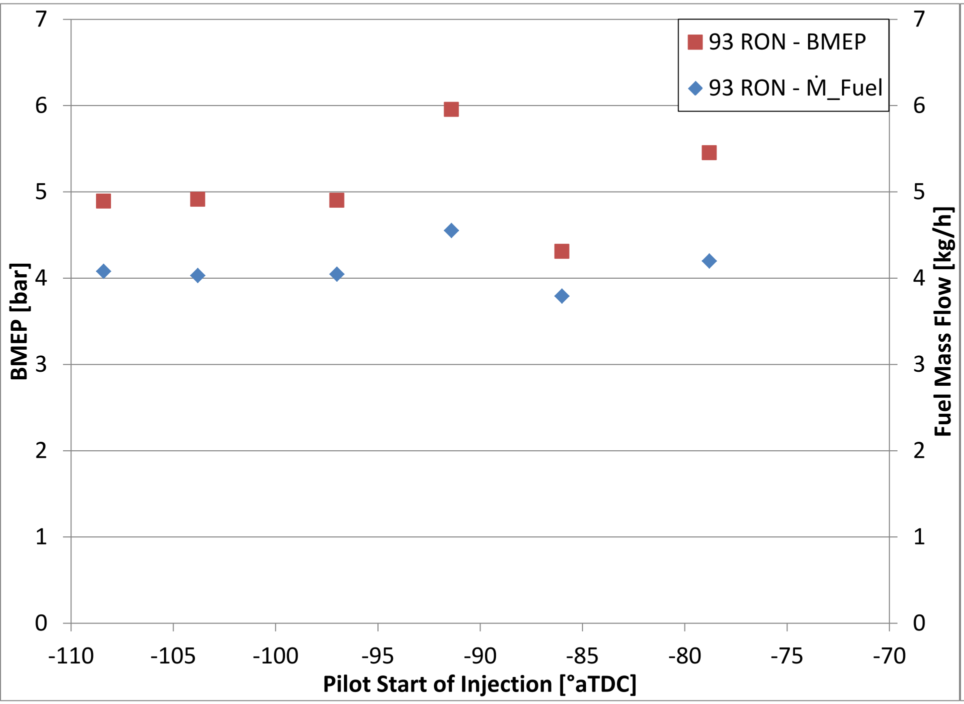
Load Range of 93 RON

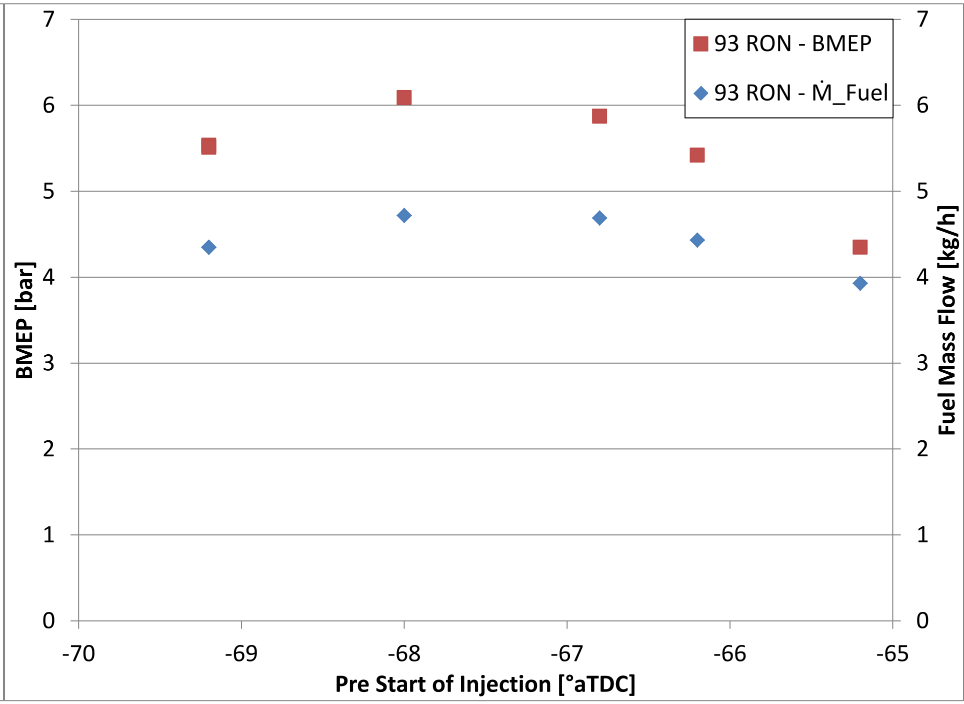


2.5 to 20 bar BMEP was achieved with a single fuel, 93 RON (87 AKI).

>99% combustion efficiency achieved from 2.5 to 20 bar BMEP.

Injection Timing Sweeps





Pilot injection timing sweep caused unexpected increases and decreases in both BMEP and fuel mass flow.

Pre injection timing sweep over a narrower range showed similar behavior as pilot timing sweep.

Cause believed to be wave harmonics in fuel injection system.

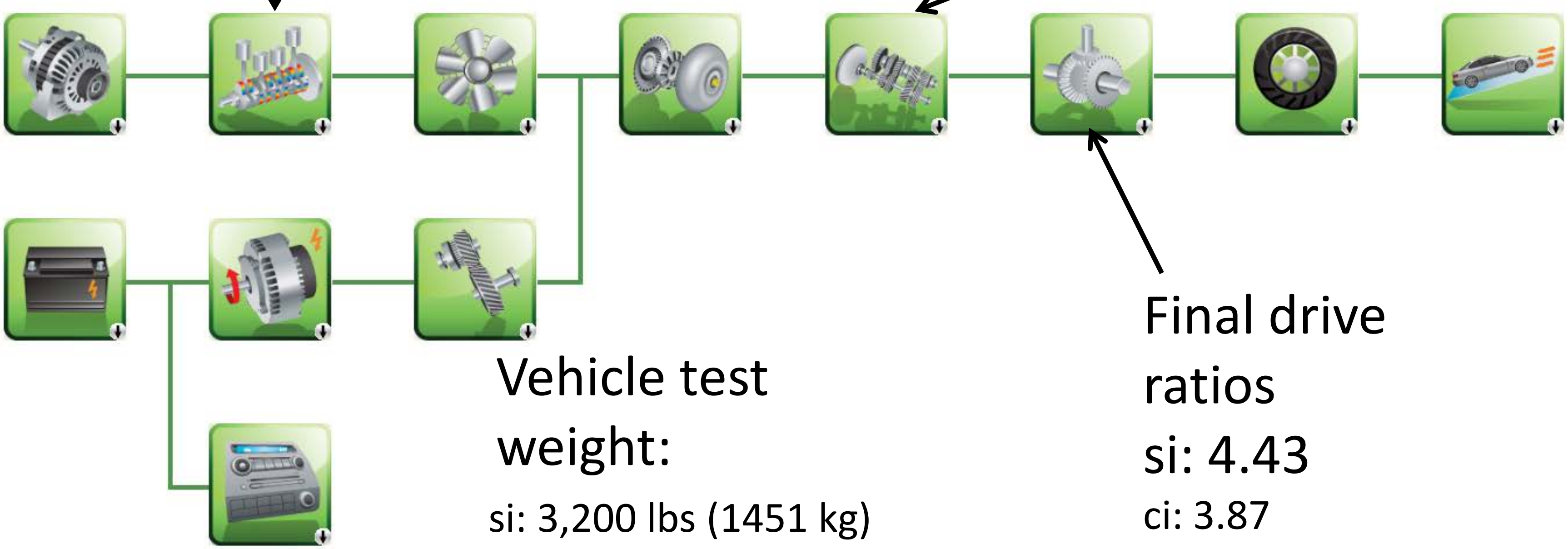
Autonomie Simulations for LTC engine compared to PFI and DISI engines

Engine, Gearbox, Final Drive and Test Weight Defined for Each Vehicle

si: PFI (US Drive reference)
2.2L SIDI
ci: 1.9L LTC

Automatic transmission ratios

si	4.15	2.37	1.56	1.16	0.86	0.69
ci	4.04	2.37	1.56	1.16	0.85	0.67



Vehicle test weight:

si: 3,200 lbs (1451 kg)
ci: 3,310 lbs (1501 kg)

Final drive ratios

si: 4.43
ci: 3.87

All vehicles sized to meet the same VTS (0-60mph in 9sec and grade)

LTC Engine Shows Significant Fuel Economy Improvement over PFI and DI

Fuel Consumption

	UDDS [L/100km]	HWFET [L/100km]	Combined [L/100km]	**Improvement over PFI [%]**	**Improvement over SIDI [%]**
PFI	9.7	6.7	8.4		
SIDI	8.5	6.0	7.4	**11**	
LTC Engine	8.0	5.6	6.9	**18**	**7**

Fuel Economy

	UDDS [mpg]	HFWET [mpg]	Combined [mpg]	**Improvement over PFI [%]**	**Improvement over SIDI [%]**
PFI	24.2	35.2	28.2		
SIDI	27.6	38.9	31.7	**13**	
LTC Engine	29.6	42.4	34.2	**21**	**8**

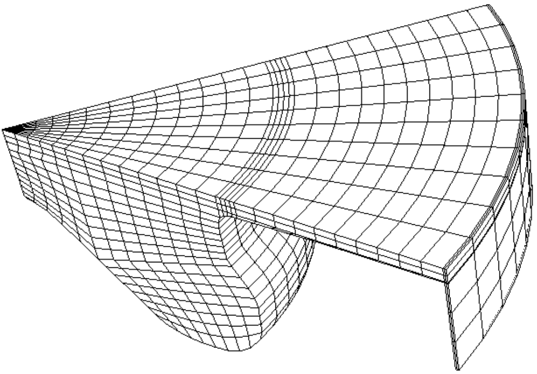
KIVA Simulations from UW-Madison ERC

Overview of KIVA Simulations

- GM 1.9L 4-cylinder engine, operated at 2 bar and 5 bar BMEP load conditions and at 1500 rev/min engine speed, were validated using KIVA-3V-Chemkin Computational Fluid Dynamics [CFD] simulations.
- Experiments were performed using two different fuels, i.e., 75 RON and 93 RON.
- From the motoring validations, it has been observed that the effective compression ratios [CR] of all four cylinders are somewhat different, mainly due to the difference in manufacturing tolerances for cylinder-to-cylinder. Less important for traditional diesel, fairly significant for LTC.
- Cylinder-to-cylinder variability issue added to the cycle-to-cycle variation made the numerical study quite challenging.
- Simulations were conducted considering the Anti-Knock Index [AKI = (RON+MON)/2] of the fuel as the Primary Reference Fuel [PRF] number, which is represented by the iso-octane [ic8h18] and n-heptane [nc7h16] chemistry.

2 bar BMEP Load Condition Using 75 RON Fuel

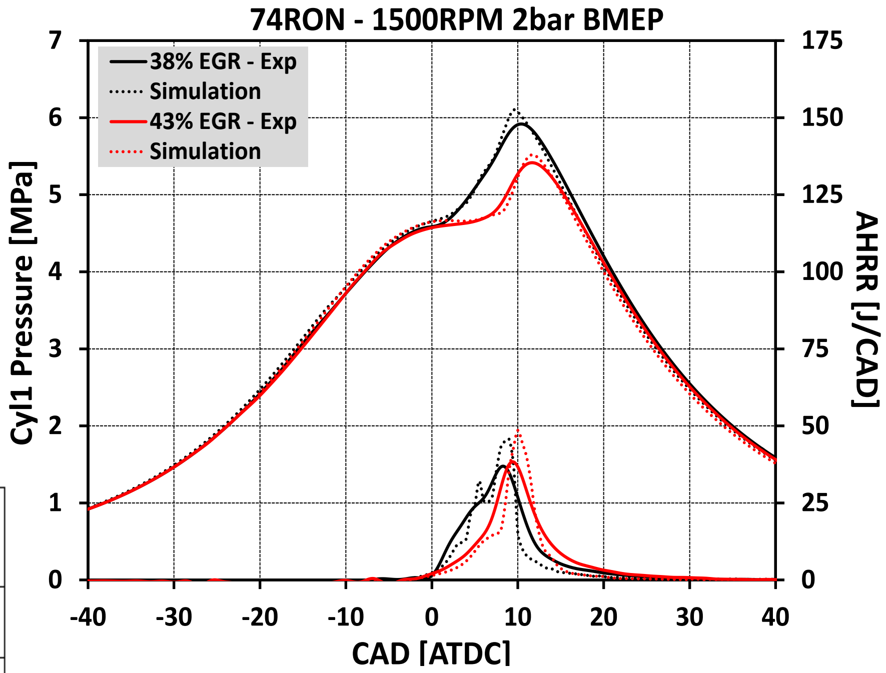
Computational grid at TDC:



Effective CR of all 4 cylinders:

	Effective CR
Cylinder1	17.83
Cylinder2	17.18
Cylinder3	17.65
Cylinder4	16.45

Experimental and predicted pressure and heat release using 75 RON fuel:



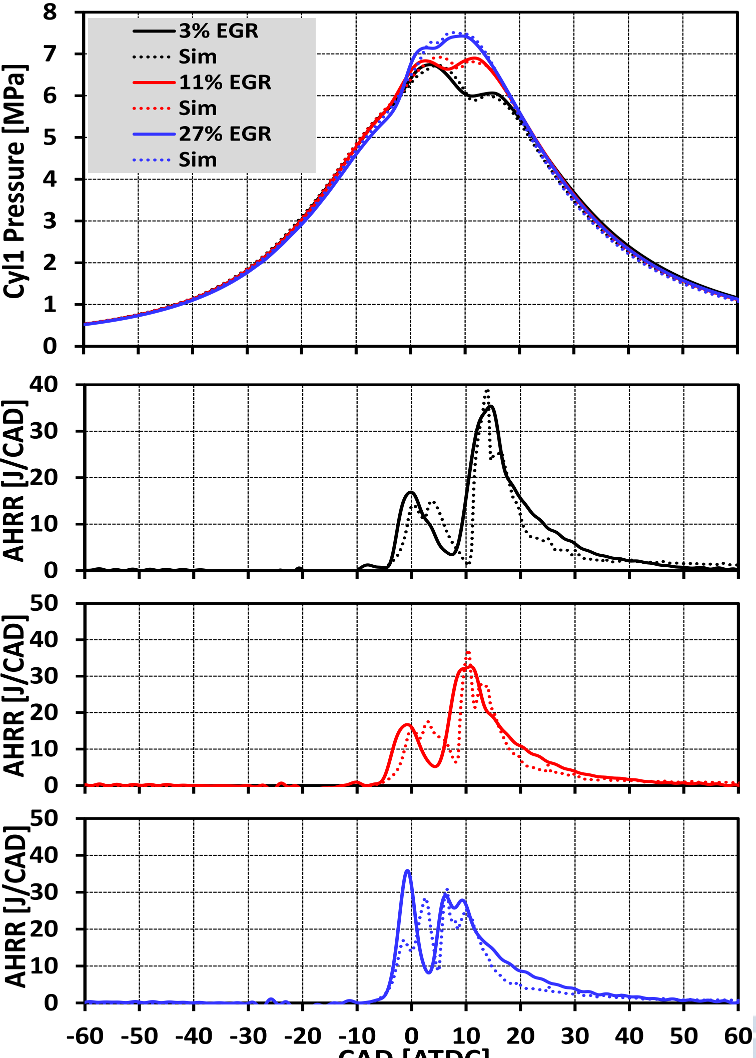
Performance comparison between experiments and simulations at 2 bar BMEP:

	P_Intake [bar]	P_IVC [bar]	T_Intake [C]	T_IVC [C]	Specific NOx [g/kW-hr]	Specific UHC [g/kW-hr]	Specific CO [g/kW-hr]	η_ Comb	ISFC [g/kW-hr]	BSFC [g/kW-hr]
Exp - 38% EGR	1.046	-	81.396	-	0.231	5.701	6.218	0.978	193.093	316.450
Sim	-	1.07	-	117	1.53	11.83	11.9	0.936	203.175	-
Exp - 43% EGR	1.036	-	74.168	-	0.092	10.302	11.391	0.963	210.420	339.154
Sim	-	1.06	-	102	0.0826	36.916	27.5	0.83	224.5	-

- NO_x, UHC and CO were over-predicted in simulations, mainly due to the cylinder-to-cylinder variations, whereas these simulations only considered cylinder 1.
- Under-predicted combustion efficiency could be due to the variations in injection parameters, which could also have a cylinder dependency.

5 bar BMEP Load Condition Using 75 RON Fuel

Experimental and predicted pressure and heat release using 75 RON fuel at 5 bar BMEP load:



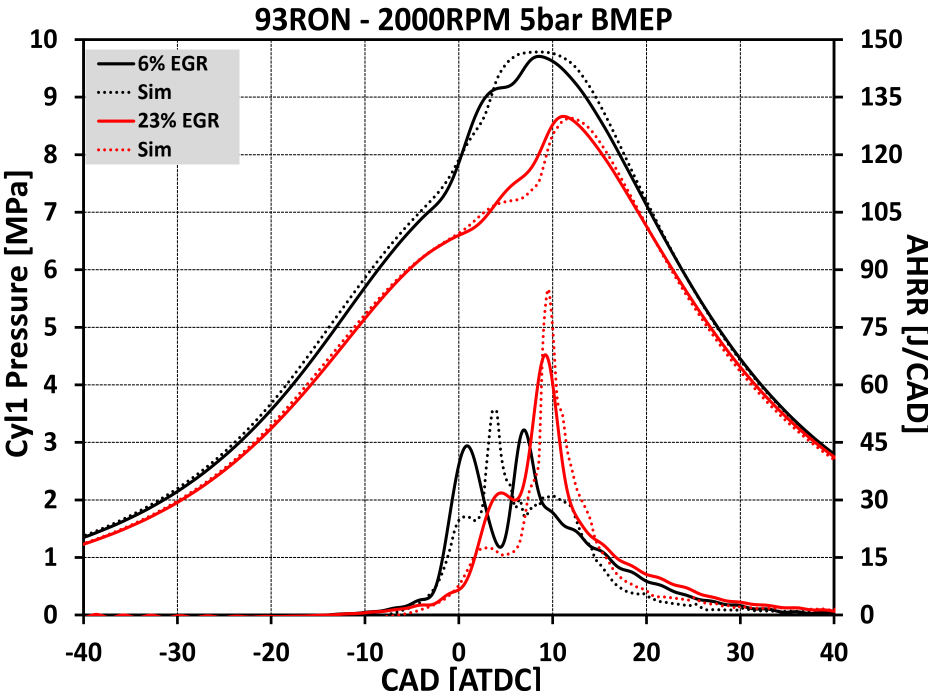
Performance comparison between experiments and simulations at 5 bar BMEP using 75 RON fuel:

	P_Intake [bar]	T_Intake [K]	Specific NOx [g/kW-hr]	Specific UHC [g/kW-hr]	Specific CO [g/kW-hr]	FSN	Soot [g/kW-hr]	η_ Comb	ISFC [g/kW-hr]	BSFC [g/kW-hr]
Exp - 3% EGR	1.196	34.004	0.858	1.646	1.957	0.310	-	0.991	193.419	227.716
Simulation	-	-	3.782	10.978	17.822	-	0.033	0.937	211.525	-
Exp - 11% EGR	1.204	43.006	0.723	1.453	1.447	0.550	-	0.992	190.863	222.910
Simulation	-	-	3.303	10.783	13.805	-	0.022	0.938	201.457	-
Exp - 27% EGR	1.201	76.824	0.402	1.273	0.962	2.640	-	0.993	180.651	217.790
Simulation	-	-	1.829	7.445	10.627	-	0.038	0.953	200.482	-

- A decrease in NO_x with increased EGR
- NO_x, CO and UHC are over-predicted as before.
- UHC was predicted mostly from the crevice region which is not well-resolved in simulations.
- Even though the soot emission is low in both experiments and simulations, both soot and NOx were higher than desired.

5 bar BMEP Load Condition Using 93 RON Fuel

Experimental and predicted pressure and heat release using 93 RON fuel at 5 bar BMEP load:



- Increased EGR raised the intake temperature, assisting the ignition of 93 RON fuel.
- Overall emission trends were captured in the simulations. However, considering the complexity of a multi-cylinder engine operation, quantitative discrepancies were found.

Performance comparison between experiments and simulations at 5 bar BMEP using 93 RON fuel:

	Injection Pressure [bar]	P_Intake [bar]	P_IVC [bar]	T_Intake [C]	T_IVC [C]	Specific NOx [g/kW-hr]	Specific HC [g/kW-hr]	Specific CO [g/kW-hr]	η_Comb	ISFC [g/kW-hr]	BSFC [g/kW-hr]
Exp - 6% EGR	500	1.49	-	61.0	-	1.315	9.207	4.767	0.961	182.138	265.203
Simulation	500	-	1.58	-	97	4.191	5.709	7.462	0.965	182.772	-
Exp - 23% EGR	500	1.38	-	71.5	-	0.363	7.096	3.219	0.971	180.700	273.940
Simulation	500	-	1.45	-	107	1.996	5.437	5.696	0.968	185.751	-

Other KIVA Observations and Future KIVA Work

- With the lowest compression ratio, cylinder 4 was the most difficult to simulate.
- Increased temperature and lowered EGR ratio were found to have similar effects on in-cylinder combustion.
- Low load operation in the multi-cylinder engine is very sensitive to the fuel splits and SOI timings.
- For triple-pulse operation, an advanced third injection is effective in lowering the simulated soot.
- To maintain the combustion phasing, a higher RON fuel required a different injection strategy to introduce more premixing.

With minimum cycle-to-cycle variation in the experiments and proper fuel representation in the computation, all four cylinders should be simulated individually, and the average emissions should be compared to the experiments for better predictions

Project Future Work

- Expand minimum load limit with 93 RON fuel
- Explore more boost pressure effects at medium/high load
  - Connect with John Dec's work on ignition/boost
  - HP EGR makes this a challenge at low loads
- Study effects of injection timing on mixture preparation before auto-ignition
- Work towards running the engine in transient conditions
- Reduce NO_x emissions and characterize tradeoff with optimum BSFC
- Begin to characterize particulate emissions
  - SMPS
- Exploring the possibility of VVA system with Eaton

Summary

- Wide range of loads explored using pump style gasoline (87 AKI)
  - 2.5 bar to 19 bar BMEP
- Significant efficiency improvements over last year's AMR presentation, especially at low load.
- Cetane enhancer (EHN) utilized in low concentration to study its influence upon this combustion approach
  - Ease of ignition is enhanced but more characterization is needed to understand the influence.
- KIVA simulations have made considerable progress to match engine results – single cylinder combustion matching produced quite good agreement
- Simulated vehicle using this LTC approach achieved a 21% fuel economy improvement over PFI engine

Technical Back up slides

Efficiency Equations

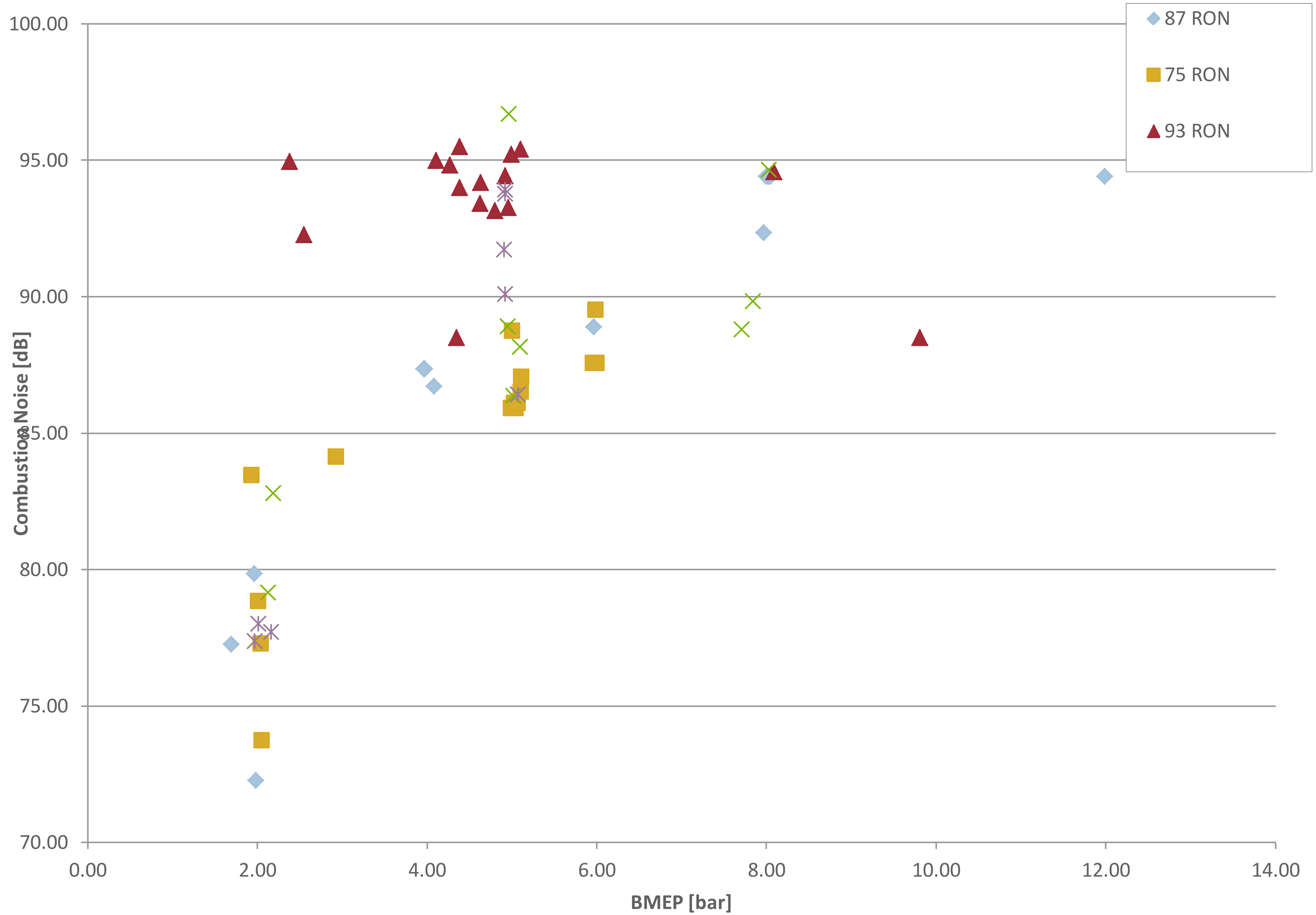
$$\eta_{Combustion} = 1 - \frac{\dot{m}_{CO} * Q_{LHV,CO} + \dot{m}_{HC} * Q_{LHV,HC}}{\dot{m}_{fuel} * Q_{LHV,fuel}}$$

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

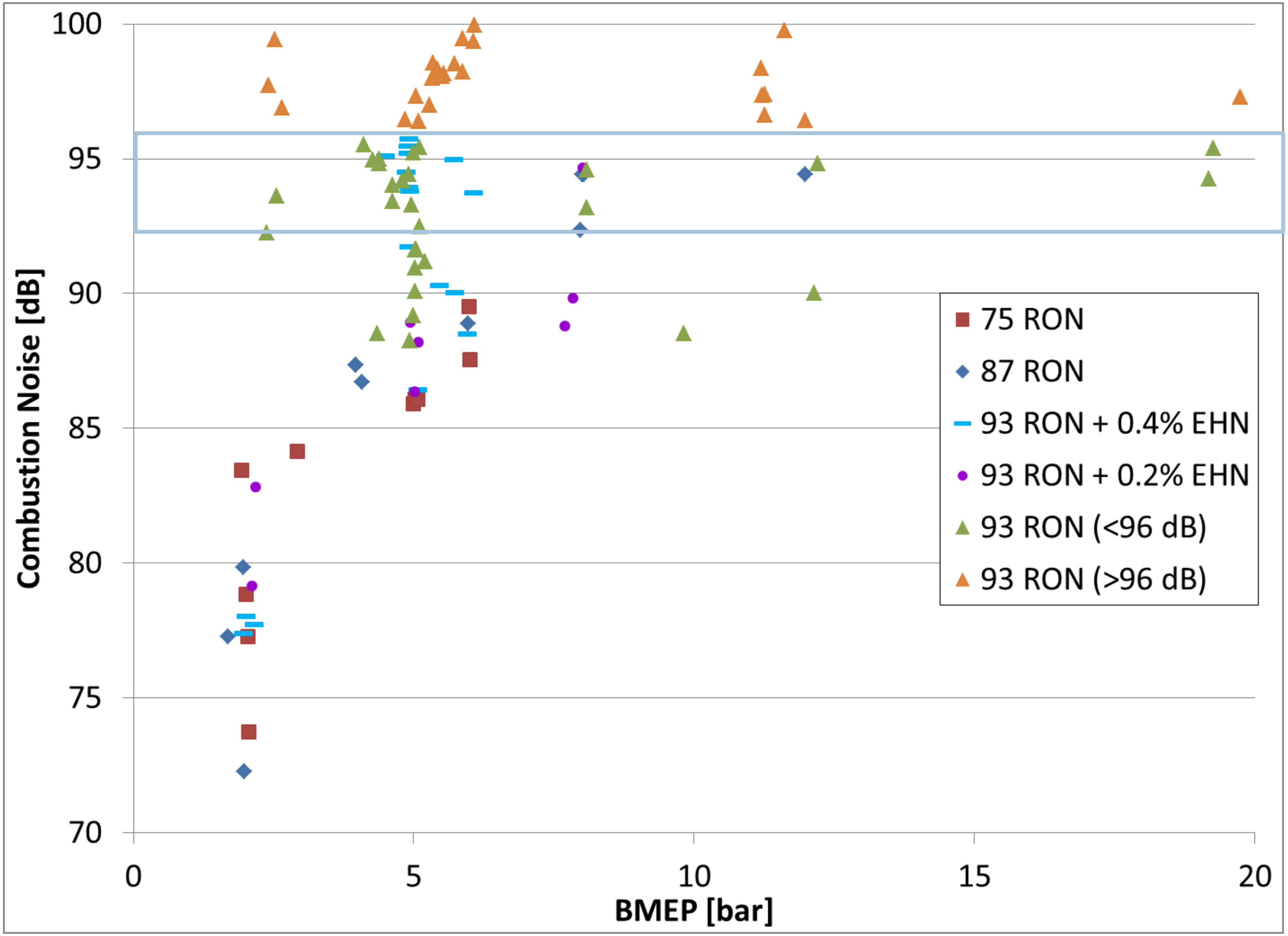
$$\eta_{Gas\ Exchange} = \frac{IMEP_{Net}}{IMEP_{Gross}}$$

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

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



87 RON
75 RON
93 RON
100.00
95.00
90.00
85.00
80.00
75.00
70.00
Combustion Noise [dB]
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
BMEP [bar]


100
95
90
85
80
75
70
Combustion Noise [dB]
0
5
10
15
20
BMEP [bar]
75 RON
87 RON
93 RON + 0.4% EHN
93 RON + 0.2% EHN
93 RON (<96 dB)
93 RON (>96 dB)