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Diesel HCCI with External Mixture Preparation

Presented by:

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DEER 2004

Overview

- DEER 2002 – “We think we can do external mixture formation HCCI, but we have no proof.”

- DEER 2003 – “We did external mixture formation, but our smoke numbers are a bit high.”

- DEER 2004 – “We’ve got excellent smoke and NO_X, we’ve got a combustion model, and are starting multi-cylinder testing. But what good is external mixture formation?”

External HCCI with Diesel?

- Diesel HCCI with external mixture formation has typically led to poor results:
  - A 2001 report to the US Congress indicated that intake air preheating (>100 C) and low compression ratios (8:1) were necessary
- These results are not inherent to external mixture formation
  - High temperatures needed fuel evaporation
  - Low compression ratios to delay SOC
  - This is a result of the *fuel preparation*
- As presented at DEER 2003, with proper atomization, results on par with internal mixture formation are possible:
  - Excellent NO_x (< 10 ppm)
  - FSN was higher than expected (0.1 – 0.5) for HCCI
  - Reasonable intake conditions and compression ratio (18:1)

Soot Formation Mechanism

- Primary Observation
  - Sporadic soot formation (every several cycles)
  - Observed using in-cylinder IR measurement
- Hypothesis:
  - Air flow interaction with fuel spray, which led to…
  - Wall targeting of manifold, which led to…
  - Droplet shear and induction, which led to…
  - Diffusion flame, which led to…
  - Elevated FSN and slightly higher NO_x
- Improvements in the fuel delivery system and integration were made for a second set of experiments in the Winter of ‘04

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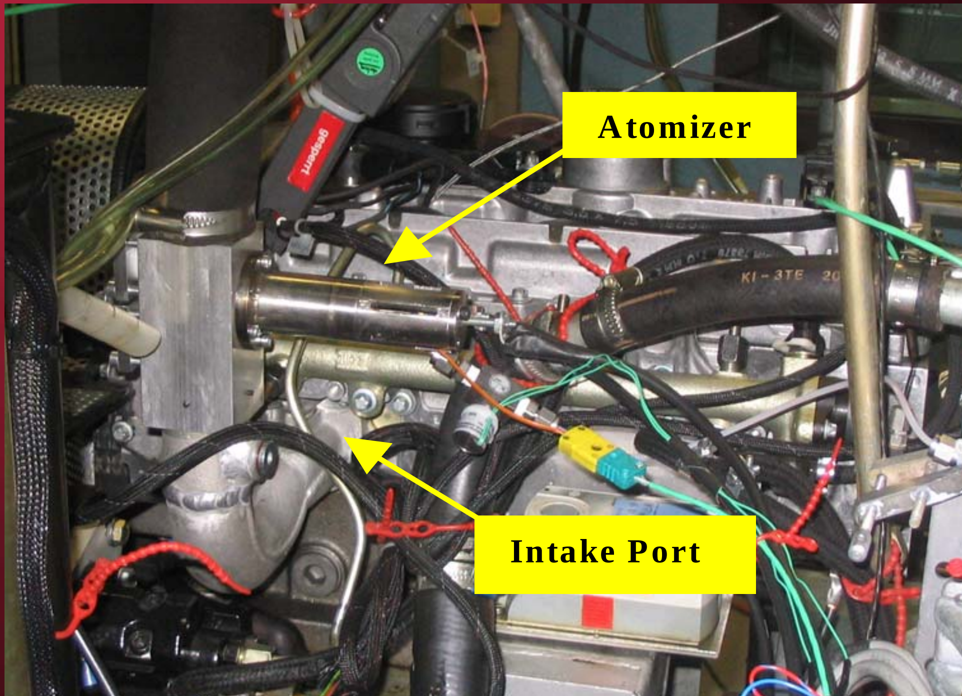
Experimental Setup

- The experimental setup is identical to that presented in 2003
  - .54 L, single-cylinder engine, 18:1 compression ratio
  - Stock cam timing and cylinder geometry, based on production engine
- Fuel delivered coaxially with the air flow

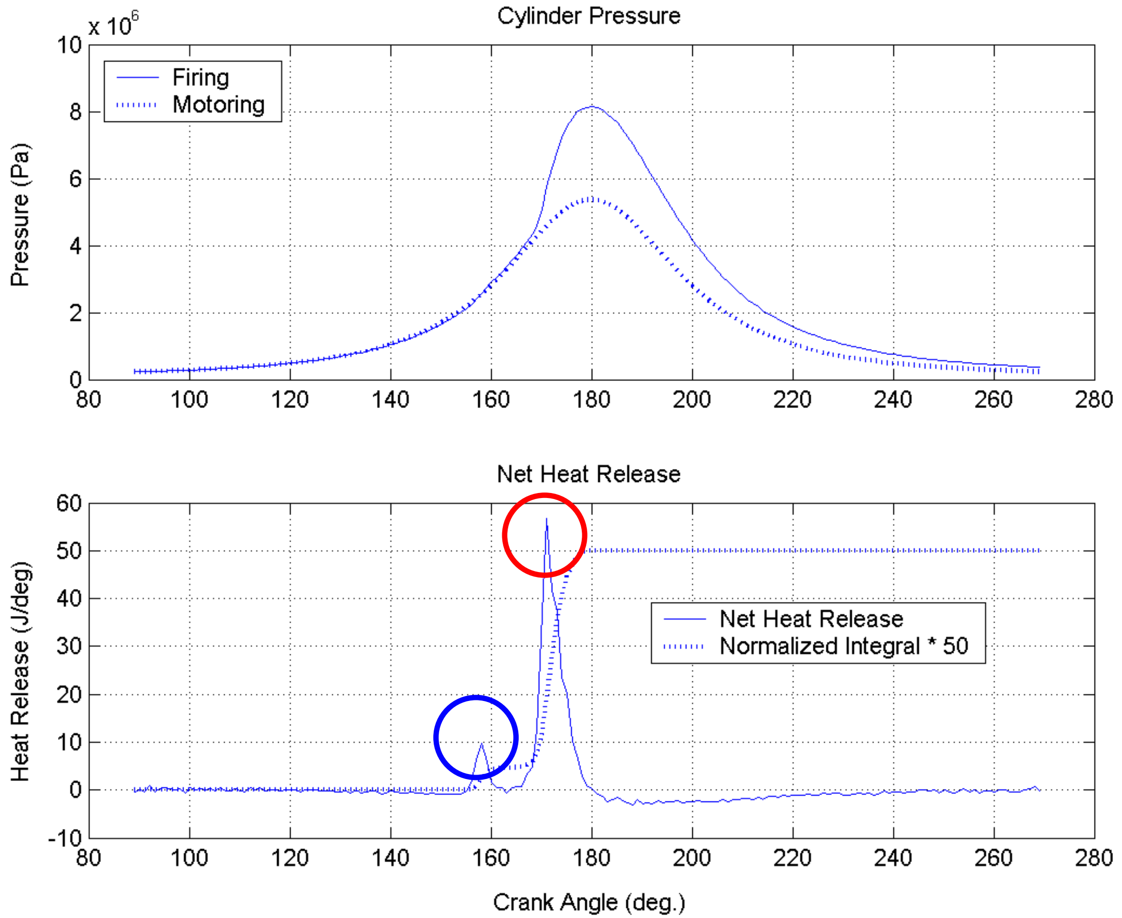
Diesel Fuel



Steps in External Mixture HCCI

1. Continuous fuel injection into intake runner
2. Highly turbulent intake process = homogenous air-droplet mixture at IVC
3. Micron-sized fuel droplets evaporate rapidly as charge temperature rises
4. In-cylinder turbulence and diffusion completes the mixing of fuel vapor with air
5. Before cool-flame chemical reactions are initiated (around 600ºC), a homogeneous charge is established
6. Combustion proceeds per the chemical processes that govern all HCCI combustion

Typical Combustion Results



- Two-stage heat release
- No EGR
- 2000 rpm

Blue = cool flame

Red = main flame

Inlet Temperature = 39°C	**NO_x = 2 ppm**
Exhaust Temperature = 220°C	**FSN = 0.00**
Boost Pressure = 1070 mbar abs.	**THC = 760 ppm**
IMEP = 2.76	**CO = 0.237%**
EGR = 0%	**CO_2 = 3.36%**
Fuel Flow = 0.680 kg/hr	**O_2 = 15.8%**

Single-Cylinder Test Plan

- Single Parameter Variations:
  - Fueling Rate
  - EGR Rate
  - Boost Pressure
  - Intake Temperature
  - Engine Speed
- Mixed-Mode Operation
  - Effect of DI injection timing w/ background of HCCI
- The following slides summarize the results

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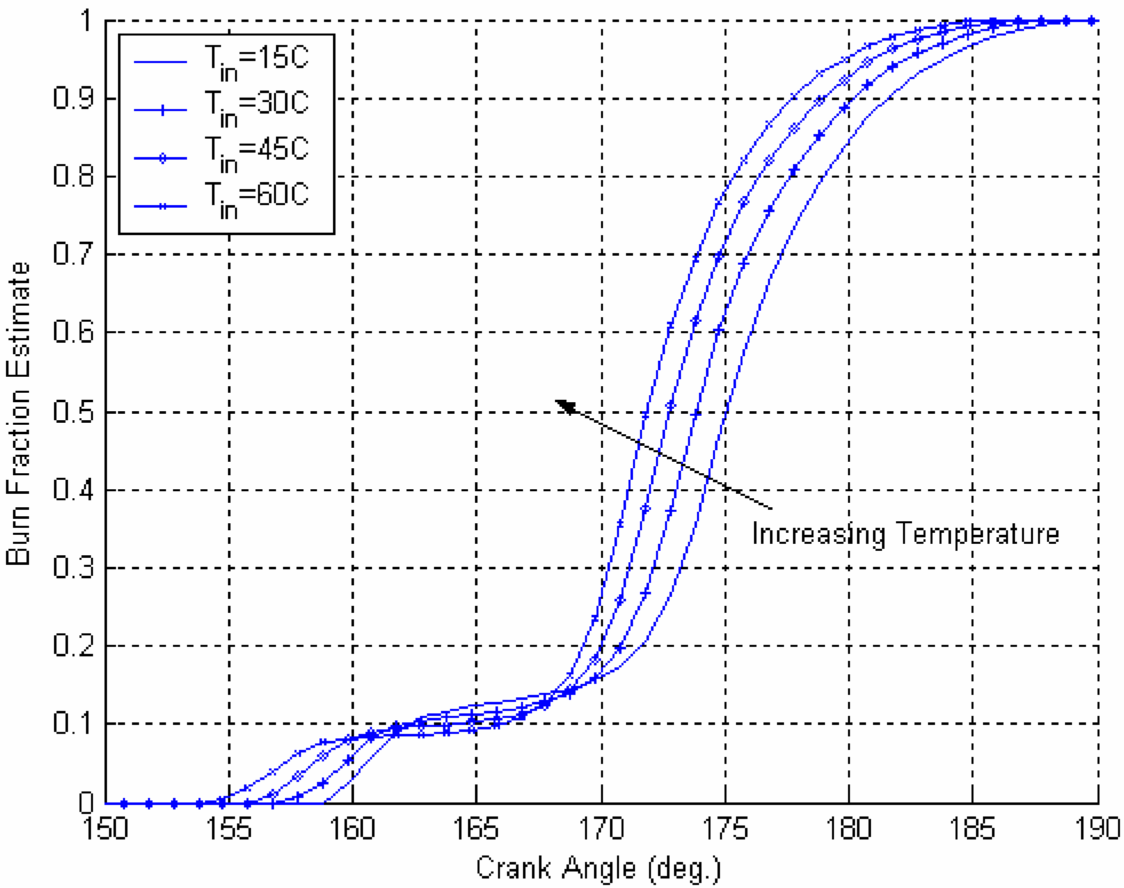
Effect of Inlet Temperature



- N = 2000 rpm, P_{boost} = 1.07 bar abs, T_{inlet} variable, EGR = 0%, fueling = constant
- Start of ignition advanced with increasing temperature; higher starting temperature means that the threshold for cool flame is reached earlier
- Resulting main combustion is largely the same but advanced a similar amount as the start of combustion

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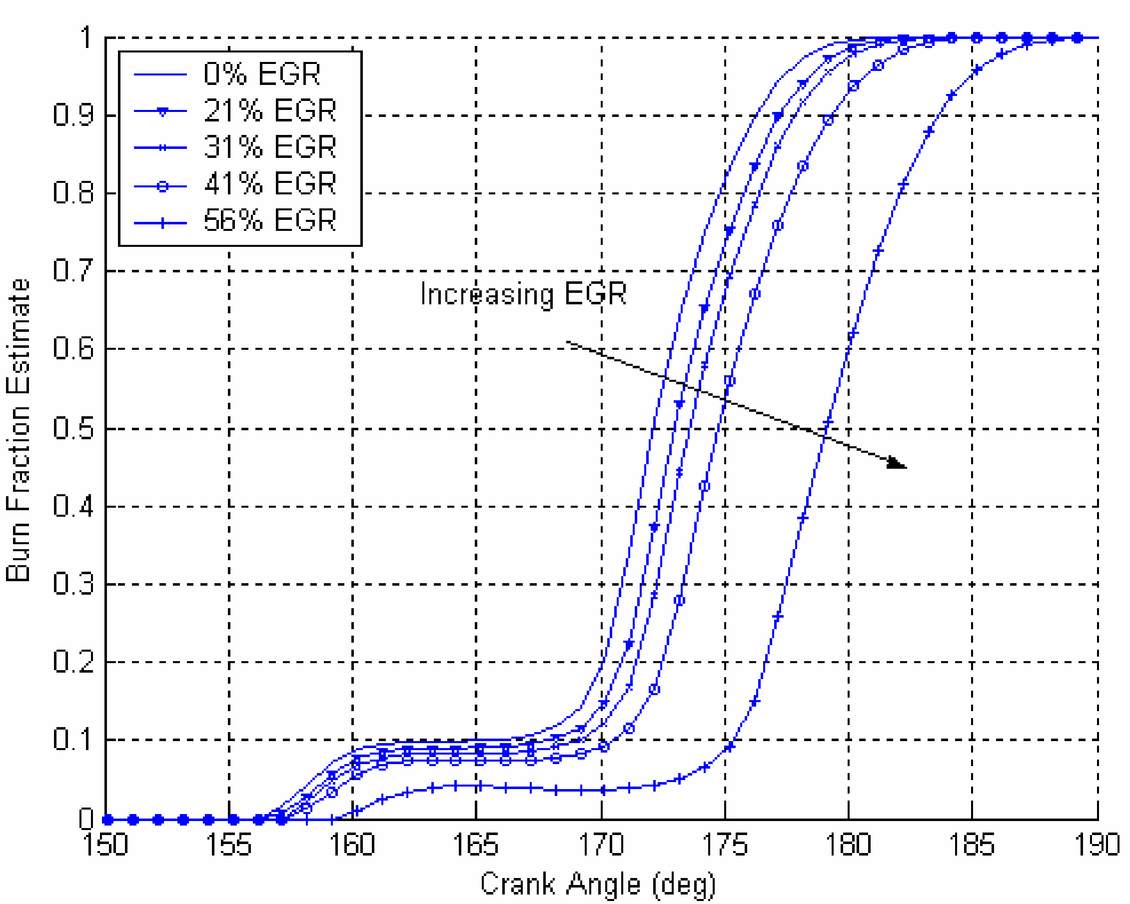
Effect of EGR



- N = 2000 rpm, P_{boost} = 1.07 bar abs, T_{inlet} = 40 °C, EGR = variable, fueling = constant $IMEP_G$
- Start of ignition delayed with EGR; threshold temperature for cool flame not reached till later because of increase in specific heat
- Less fuel burned in cool flame; chemical kinetics due to lower oxygen levels
- Higher specific heat + smaller heat release in cool flame = significantly delayed main combustion

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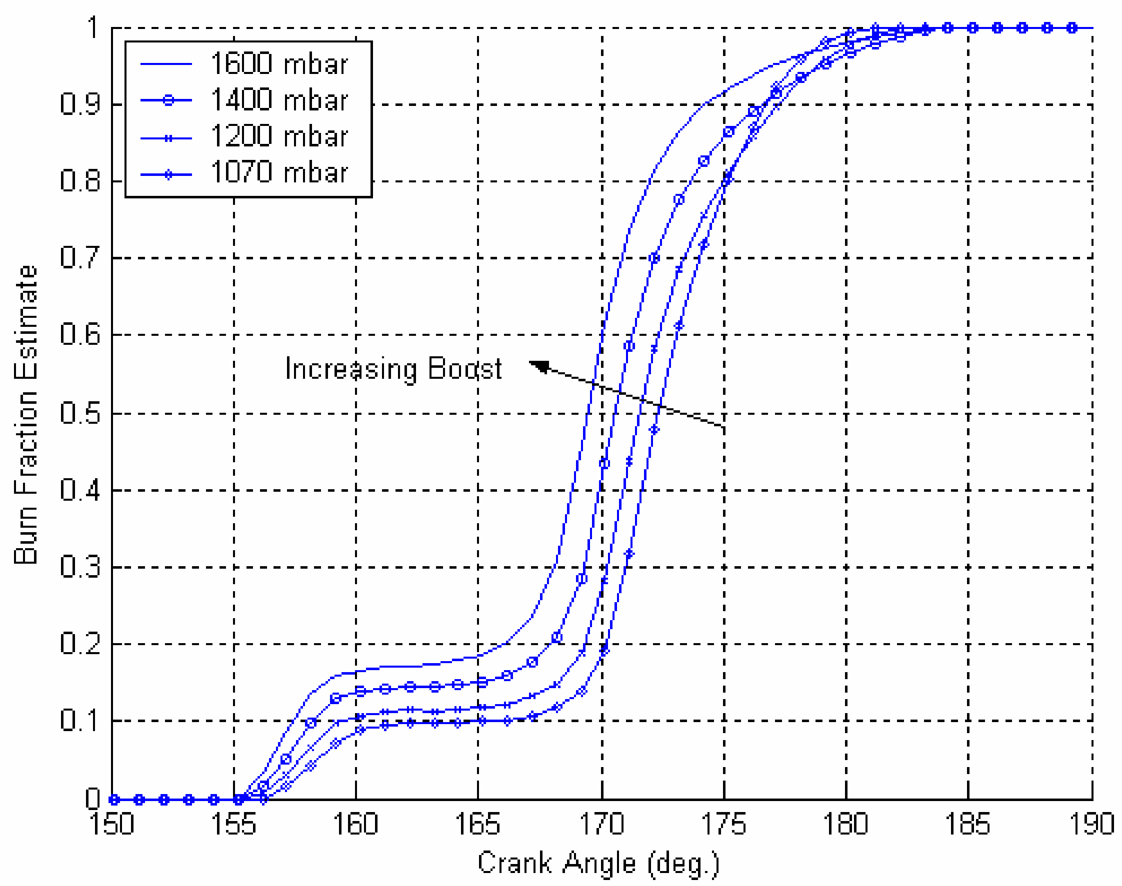
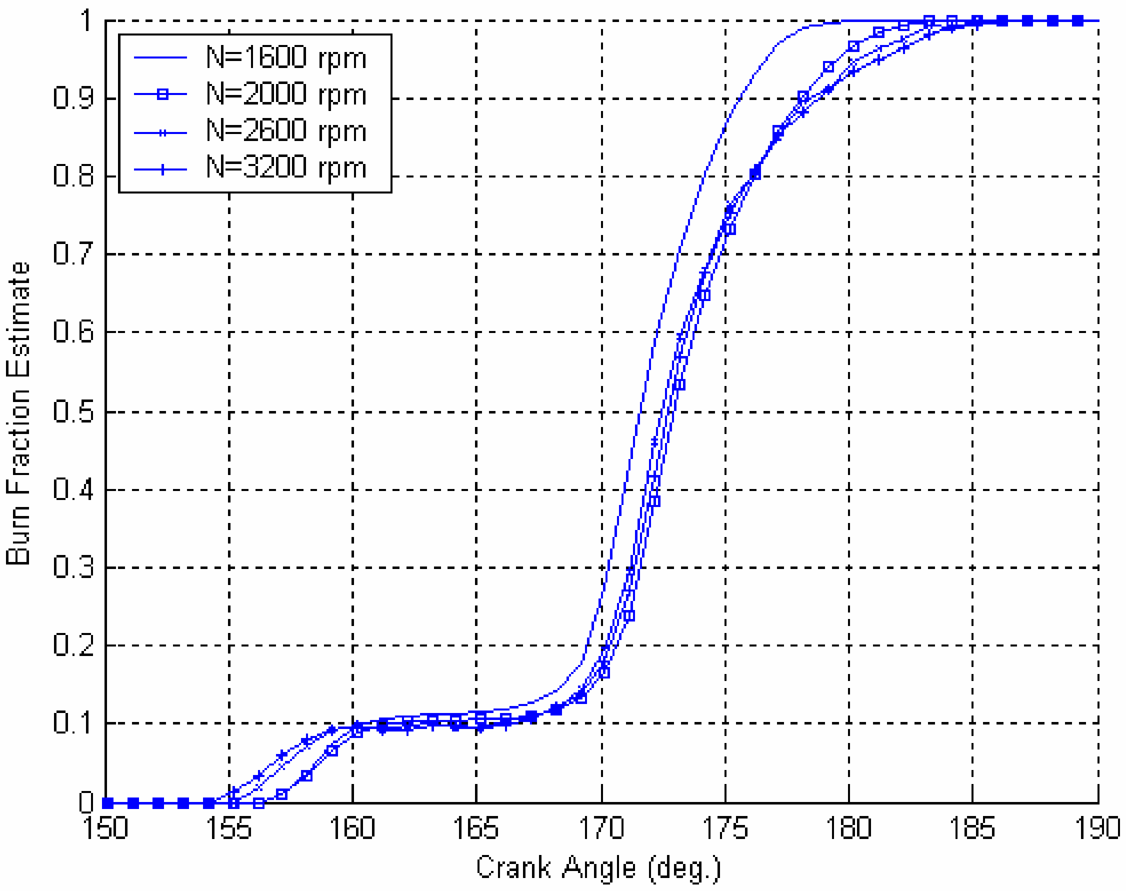
Effect of Boost Pressure



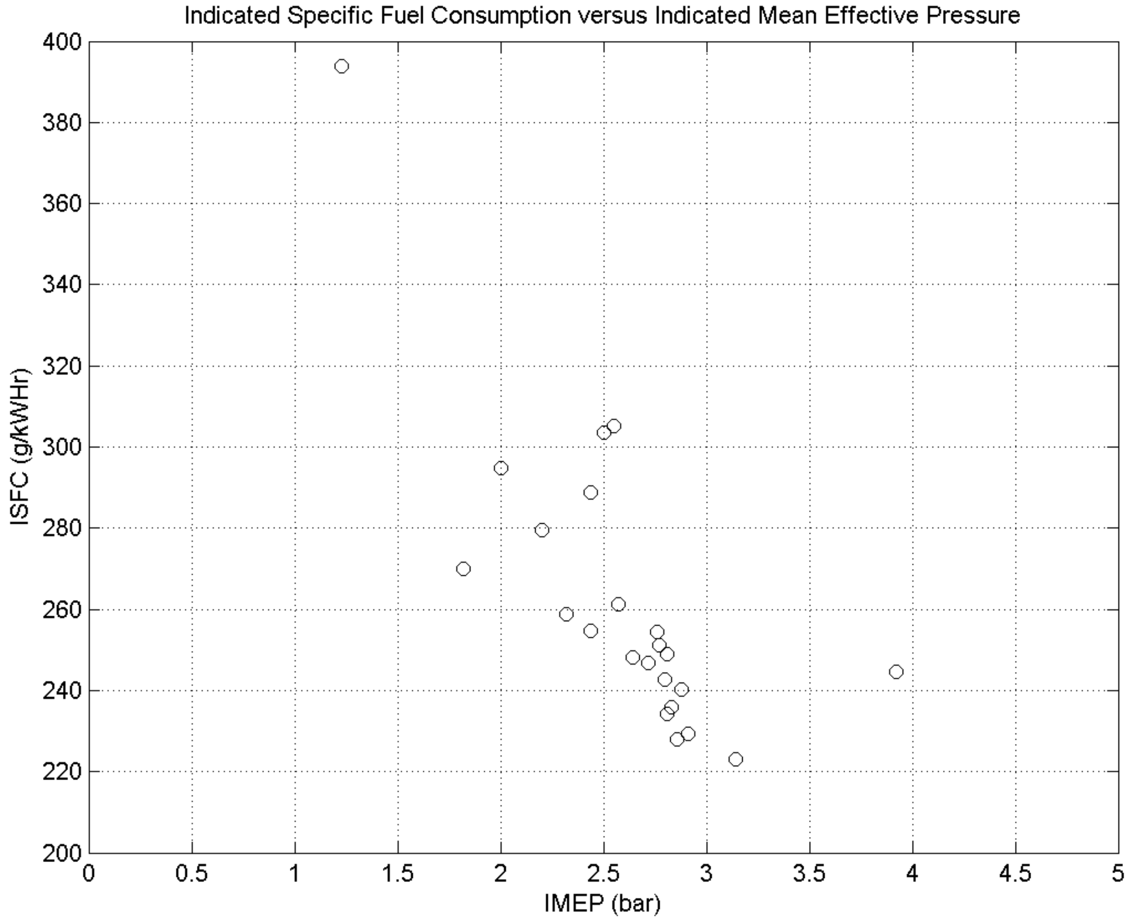
- N = 2000 rpm, P_{boost} variable, T_{inlet} = 40 ˚C, EGR = 0%, fueling = constant $IMEP_G$
- Start of ignition nearly the same
- More fuel being burned in cool flame; chemical kinetics due to higher partial pressure of oxygen
- More cool flame energy release + higher compression temperatures = advanced main combustion

Effect of Engine Speed



- N = variable, P_{boost} = 1.07 bar abs, T_{inlet} = 40˚ C, EGR = 0%, fueling = constant $IMEP_G$
- Start of ignition similar
- Cool flame heat release similar
- Main heat release similar
- Reaction at 3200 rpm is occurring twice as fast as 1600 rpm, yet it looks very similar

ISFC Results



- ISFC generally improves with increasing loads
- Ranges from about 300 to 220 g/kW-hr
- Reduced CR has been shown to improve ISFC

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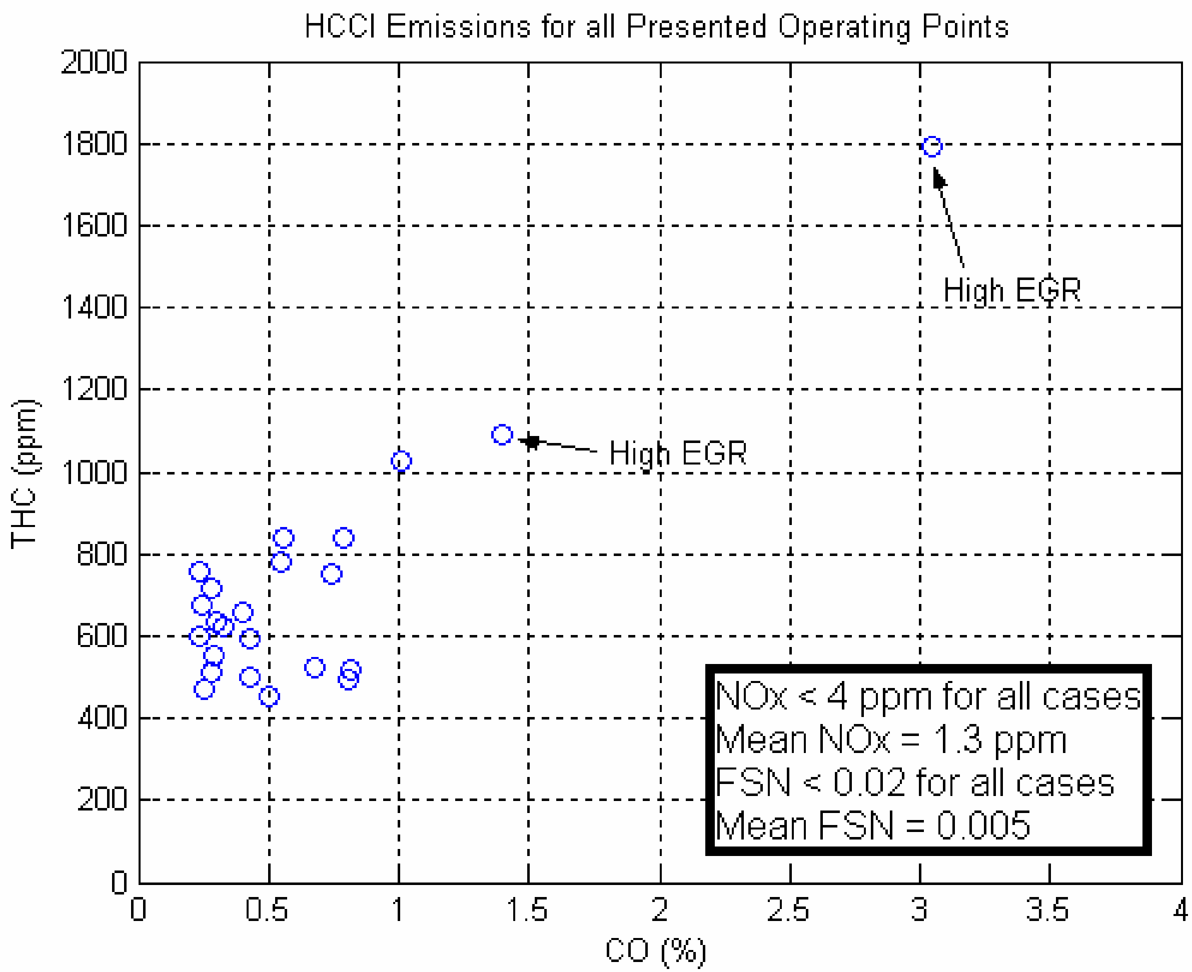
Overall Emissions Performance



- NO_x emissions:
  - < 4 ppm
  - mean = 1.3 ppm
- Smoke:
  - < 0.02 FSN
  - mean = 0.005
- Speeds from 1600 to 3200 rpm, IMEP up to 4.7 bar, varying intake conditions

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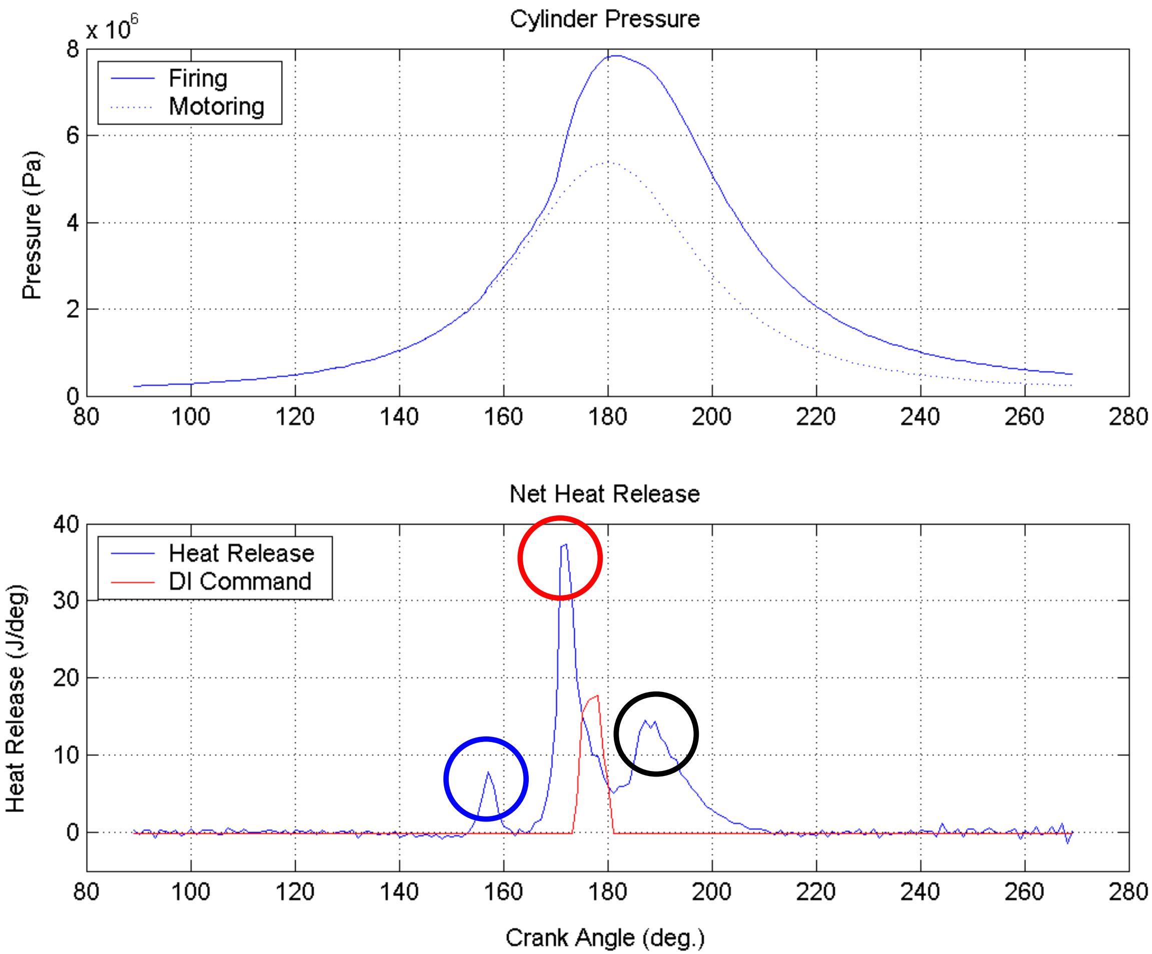
Mixed-Mode Combustion



- DI injection can be superimposed
- Moving from HCCI->mixed->DI is smooth

Cool Flame (blue)

Main HCCI (red)

DI fuel (black)

*For more info on single-cylinder results, please contact me for a copy of a recent paper

Combustion Modeling

- Model Type:
  - Zero-Dimensional, Single-Zone model
- Key Equations:
  - Energy Balance
  - Ideal Gas Law
  - Woschni heat transfer model
  - Arhenius Equation for start of cool flame
  - Temperature Threshold for start of main flame
  - Wiebe Functions for combustion model

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Model I/O

- Model Inputs:

  Fuel, air, and EGR mass; pressure and temperature at IVC

- Model Outputs:

  Primary = cylinder pressure and temperature

  Secondary = IMEP, combustion inefficiency, heat transfer, etc…

Start of Ignition

- Start of cool flame reaction – Arhenius Threshold:

$$AR(\vartheta) = \frac{A}{\omega}[O_2]^{-0.53}[Fuel]^{0.05}\rho^{0.13}\exp\left(\frac{E_a}{RT}\right)$$

$$\int_{IVC}^{\vartheta_{SOC}} \frac{1}{AR(\vartheta)}\,d\vartheta = 1$$

- Start of main flame – Temperature Threshold
  - Once mixture temperature is above a constant threshold, main flame occurs

$$T(\theta_{SOC}) = 975K$$

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Combustion Model

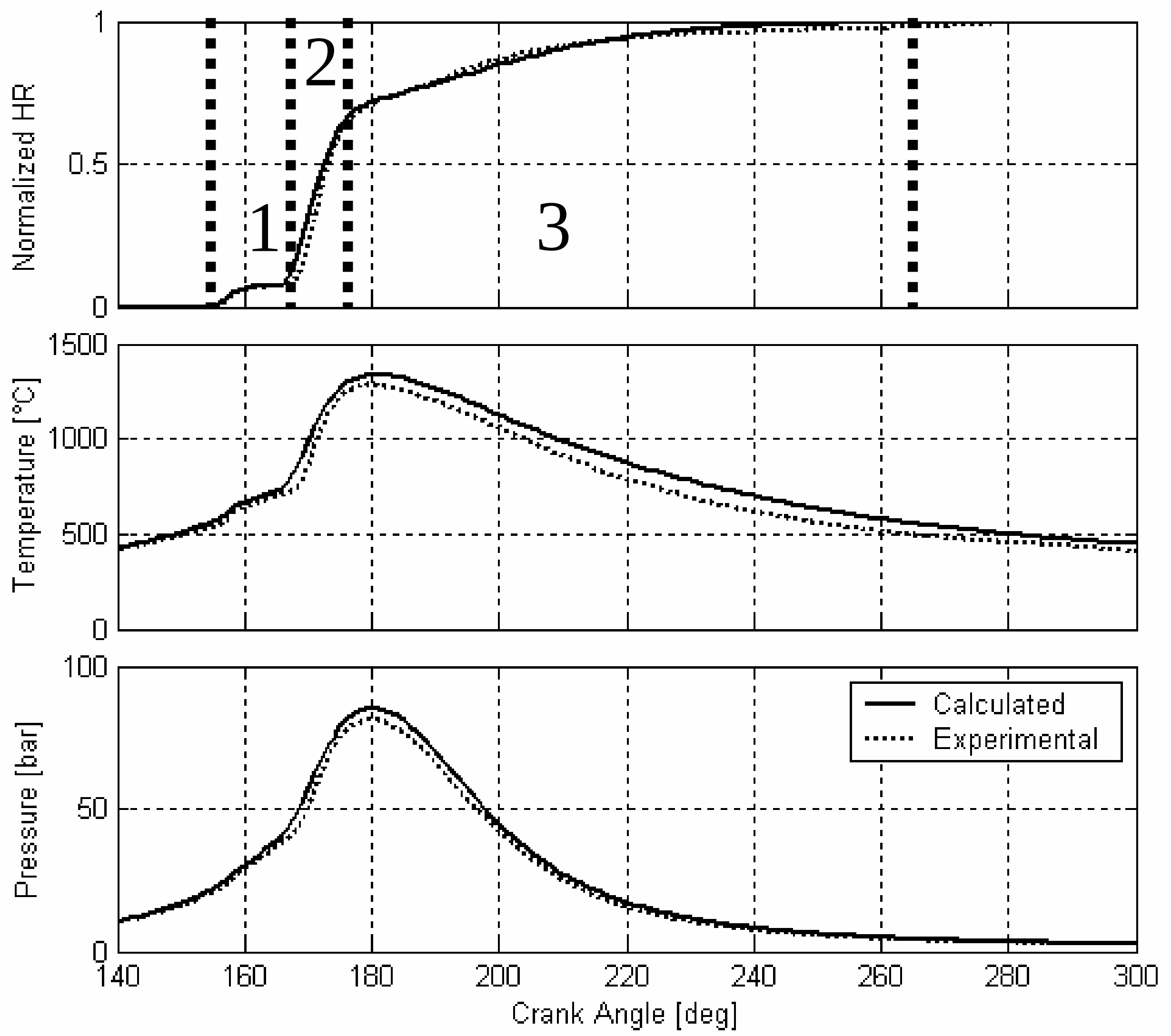
- Wiebe functions:

$$x_b(\vartheta) = \alpha x_1(\vartheta) + \beta x_2(\vartheta) + (1-\alpha-\beta)\,x_3(\vartheta)$$

$$x_i(\vartheta) = 1 - \exp\left[-a_i\left(\frac{\vartheta - \vartheta_{0i}}{\Delta\vartheta_i}\right)^{m_i+1}\right],\ i = 1, 2, 3$$

- Two Wiebe functions – initial model
  - One for cool flame, one for main combustion
  - Does not capture the long slow combusting “tail” shown in the data
- Three Wiebe functions – revised model
  - One for cool flame, one for main combustion, one for the “tail”
  - Does a good job at recreating the measured results

Model Results:



- Good agreement with measured data
- The presence of the three different “phases” of combustion is clear

1 – Cool Flame

2 – Main Combustion

3 – Slow Oxidation

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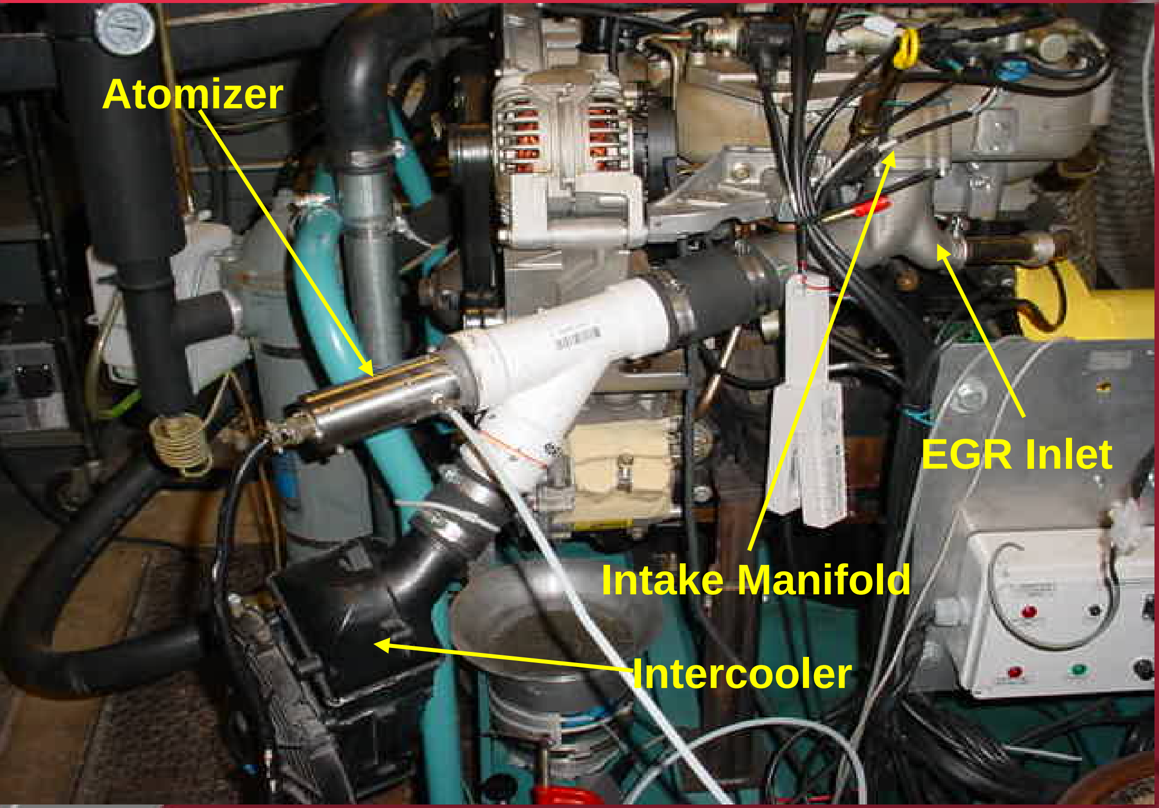
Initial Multi-Cylinder Demo



- Check if single-cylinder results transfer to multi-cylinder
- Total retrofit cost = $5.23 + atomizer
- NOx < 10 ppm
- Brake Torque = 30 ft-lb
  - Increased until audible knock

	TORQUE (ft-lb)				MEP (bar)	
RPM	motor	brake	"indicated"	FMEP	BMEP	"IMEP"
1000	-21	30	51	1.4	2.0	3.4
1500	-24	23	47	1.6	1.5	3.2
2000	-26	20	46	1.7	1.3	3.1

Multi-Cylinder Testing Plans

- Just started multi-cylinder engine testing on 2.5 L engine
  - Upgraded EGR system, variable intercooling, VGT
  - Cylinder pressure measurements, emissions measurements, air loop measurements
  - Look for results in the near future
- Research Goals:
  - Feed more data into combustion model
  - Explore methods to control combustion phasing
  - Explore effect of engine speed on combustion

Why External Diesel HCCI?

- As a Research Tool:
  - Arguably, it is as homogeneous as you will get with diesel
  - Allows direct comparison of combustion of other fuels (gaseous and more volatile fuels) to diesel fuel or other heavy fuels
- As a Commercial Technology: Who Knows?
  - Requires no modification to DI combustion system - the DI system stays optimized for DI combustion
  - Mixed-mode operation is as simple as DI only operation
- Given the success of DI-based HCCI, there is not a clear case for external mixture formation over internal in *today's engines*

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Today's Diesel Engine

- High Torque * Modest Speed = Acceptable Power
- High Torque operation comes from turbocharging
- Speed limitations in diesels:
  - Fuel must mix with air for combustion, which is due to mainly:
    - Air-Fuel mixing due to injection spray
    - Air-Fuel mixing due to cylinder motion
  - At some engine speed, there simply is not enough time to get the fuel and air mixed and burned near TDC

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Tomorrow's Diesel Engine?

- A Dedicated, External, Mixture Formation, HCCI Engine
  - Modest Torque * High Speed = Acc
  - 8 bar BMEP * 6000 rp
- Modest torque is possi
- External Mixture HC
  - Fuel mixing is
  - There is no re
  - Instead, combu
  - Based on previo pm
    - Assuming th rpm the main combustion
    - However, ther rpm
- Because it i metric
    - A p mixed air engine will see nearly the same pressure temperature history as in a small with identical CR
    - he main factor in this style of HCCI combustion is simply pressure-temperature

Port fuel injection?
Low torque, high speed?
No common-rail?
High CO and HC?
Reduced compression ratio?

Sounds like some kind of
gasoline conspiracy to me…

What Type of Vehicle?

- Benefits already demonstrated for series diesels
  - Delivery vehicles, city busses, locomotives, ships
- Series flexibility allows one to “tame” the HCCI combustion by controlling transients and speed-load operating points
- Potential Benefits:
  - Low NO_x and PM w/o aftertreatment – even lower w/ aftertreatment
  - Oxidation of CO and HC possible with current DOC technology
  - Hybridization gives control over exhaust temperatures – possible to keep it above catalyst light off temperature
  - Fuel economy should be acceptable – HCCI may lose some efficiency, but hybridization could get back to diesel only fuel economy
- Proof of concept tests could be done simply on a dyno with a CR reduced engine (CR ≈ 16:1)
  - A series hybrid, is after all, basically a engine on a dynamometer

Contributors

Academic:

- Ohio State University (CAR): Prof. Yann Guezennec, Prof. Giorgio Rizzoni, Marcello Canova, Renaud Garcin, Adam Vosz, David Dumbauld, Shawn Midlam-Mohler
- University of Stuttgart (FKFS): Prof. Michael Bargende, Dr. Hans Jürgen Berner, Simon Haas

Industry/Government:

- Starting a small-scale collaboration with ORNL
- We are currently seeking research collaborations in the area of HCCI combustion.
- We are also seeking hardware resources to support our current academic HCCI research.

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