Reciprocating Internal Combustion Engines

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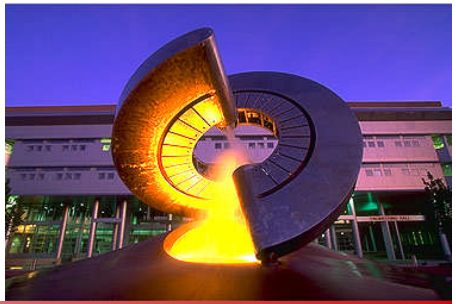
Engine Research Center,
University of Wisconsin-Madison

2012 Princeton-CEFRC
Summer Program on Combustion
Course Length: 9 hrs

(Wed., Thur., Fri., June 27-29)

Hour 8



Hour 8: Optimization and Low Temperature Combustion

Short course outine:

Engine fundamentals and performance metrics, computer modeling supported by in-depth understanding of fundamental engine processes and detailed experiments in engine design optimization.

Day 1 (Engine fundamentals)
Hour 1: IC Engine Review, 0, 1 and 3-D modeling
Hour 2: Turbochargers, Engine Performance Metrics
Hour 3: Chemical Kinetics, HCCI & SI Combustion

Day 2 (Spray combustion modeling)
Hour 4: Atomization, Drop Breakup/Coalescence
Hour 5: Drop Drag/Wall Impinge/Vaporization
Hour 6: Heat transfer, NOx and Soot Emissions

Day 3 (Applications)
Hour 7: Diesel combustion and SI knock modeling
Hour 8: Optimization and Low Temperature Combustion
Hour 9: Automotive applications and the Future

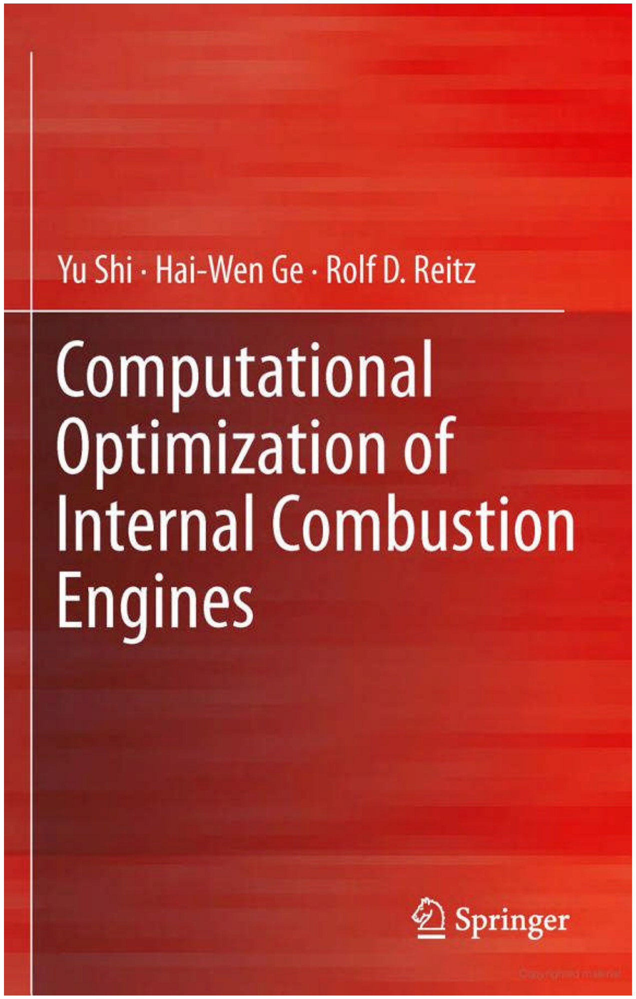
Overview of Optimization Techniques

- Enumerative or exhaustive
- Calculus or gradient-based

  "local" methods which search in the neighborhood of current design point
- Random

  "global" methods such as genetic algorithms (GA) which typically converge on a global optimum
- Univariate (one-factor-at-a-time)
- Design of Experiments (DOE)

  Two-level factorial designs (main and interaction effects)
  Response surface methods (RSM)
  Statistical model building



Yu Shi · Hai-Wen Ge · Rolf D. Reitz

Computational Optimization of Internal Combustion Engines

Springer

Genetic Algorithms

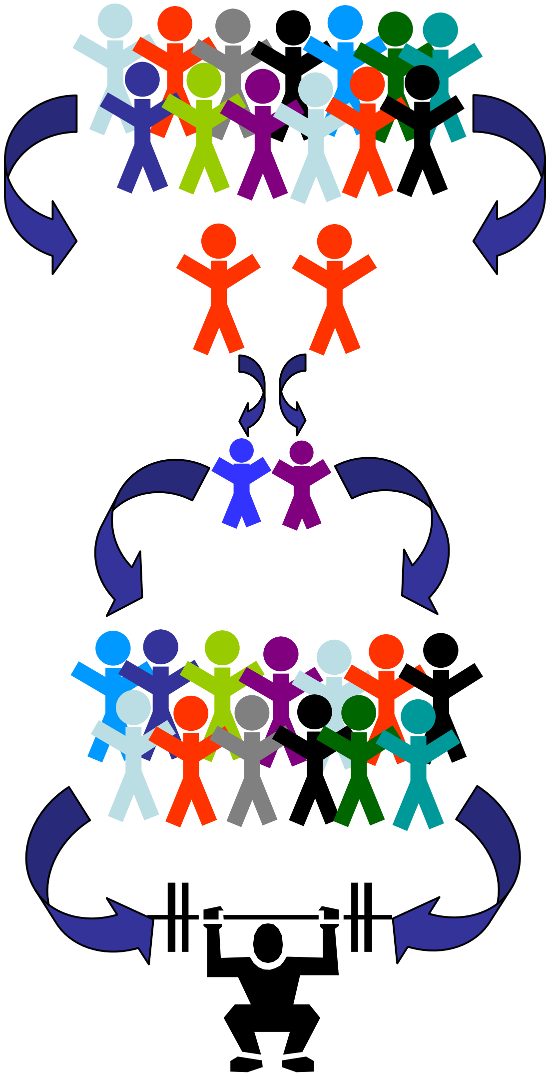
“Individuals” are generated through random selection and a “population” is produced

A model is used to evaluate the fitness of each individual

The fittest individuals are allowed to “reproduce”

A new “generation” is formed - “mutations” are allowed through random changes

The fitness criteria thins out the population and the most fit solution is achieved over successive generations

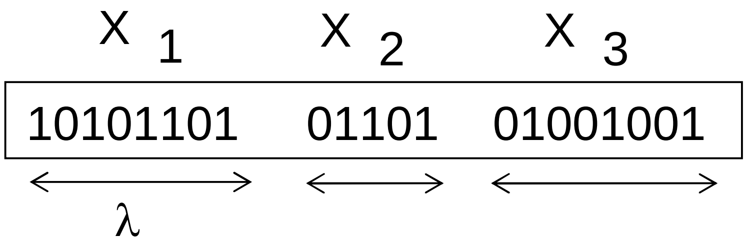


Senecal & Reitz, SAE 2000-01-1890

Implementation of Algorithm

Goldberg, 1989
Carrol, 1996
Senecal, 2000

Binary representation of parameters X - "genes"

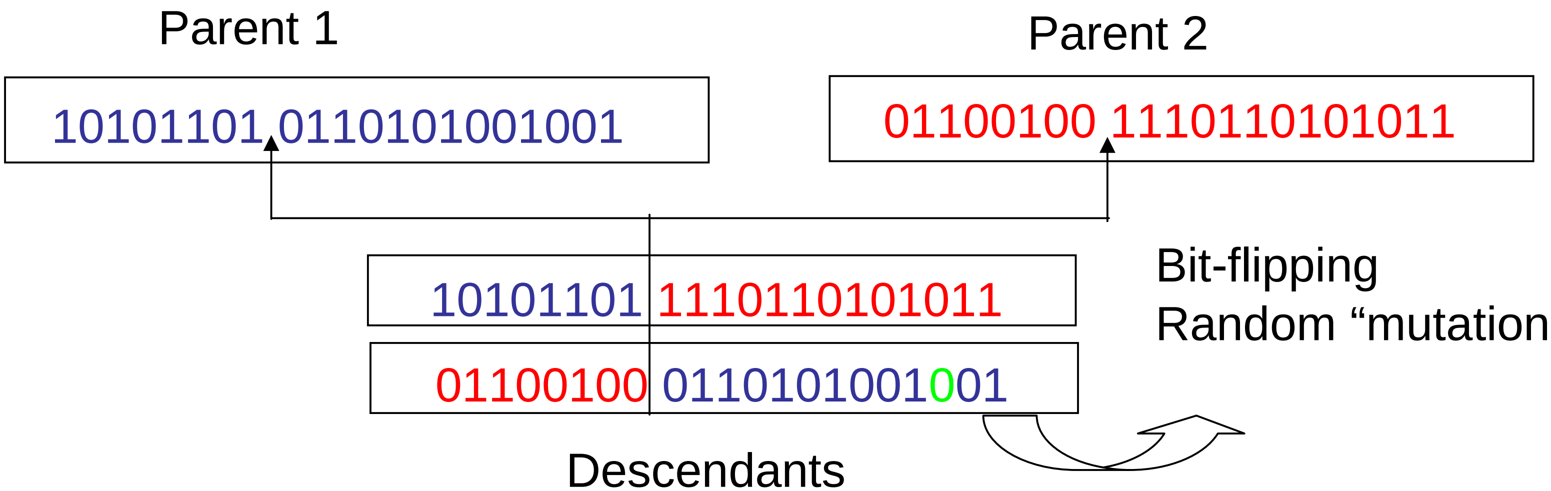


- "chromosome" gene string

Precision $$\pi = \frac{X_{i,\max} - X_{i,\min}}{2^{\lambda} - 1}$$

Evaluate merit *f* (X) for each generation member - identify "fittest"

Binary tournament selection → Bit-swapping "Cross-over"

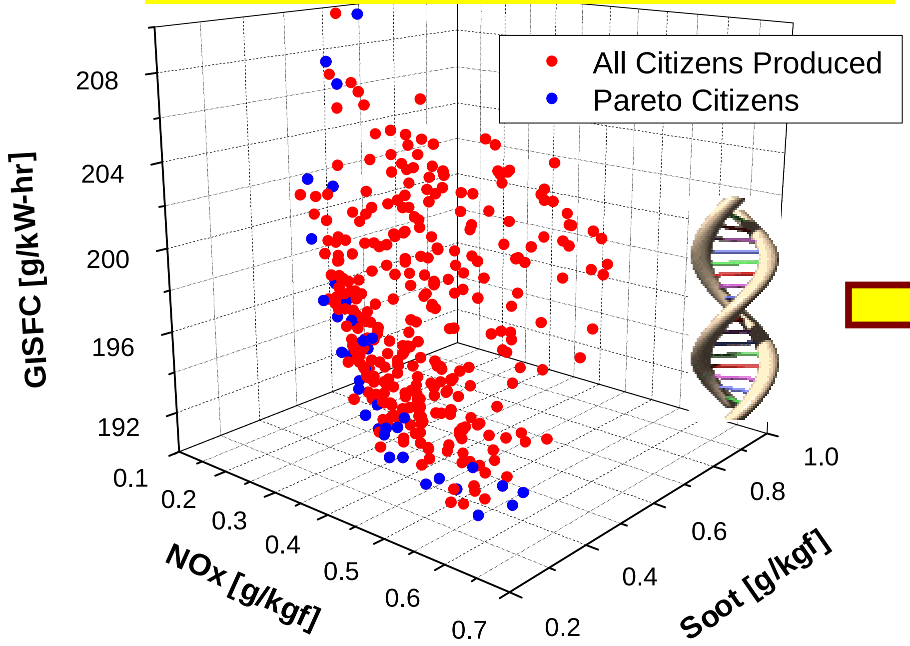


Bit-flipping
Random "mutation"

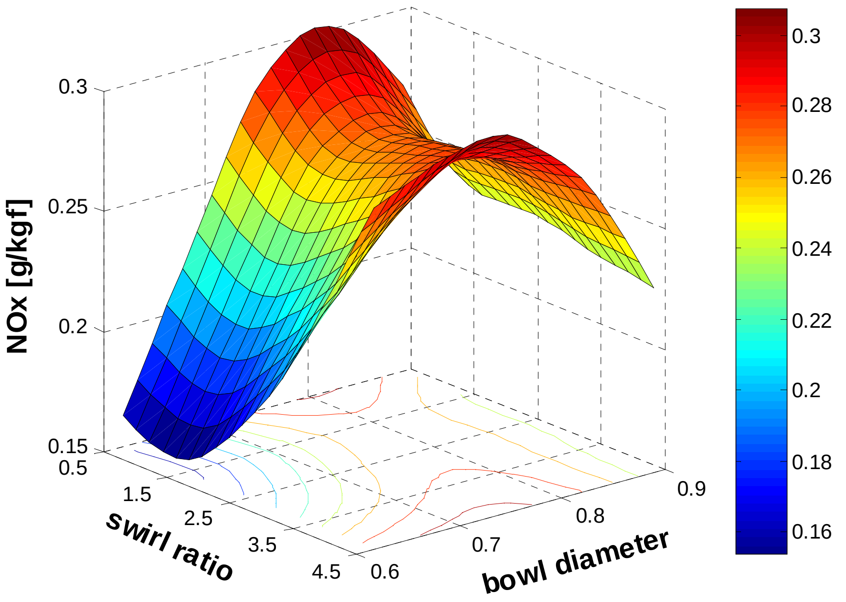
Descendants

Optimization Methodology

Multi-Objective Genetic Algorithm



Nonparametric Regression Technique



- Simultaneous optimization of many objectives [1]
- No merit function required to drive search
- Pareto front offers more information than a single optimum

Coello Coello & Pulido , 2001

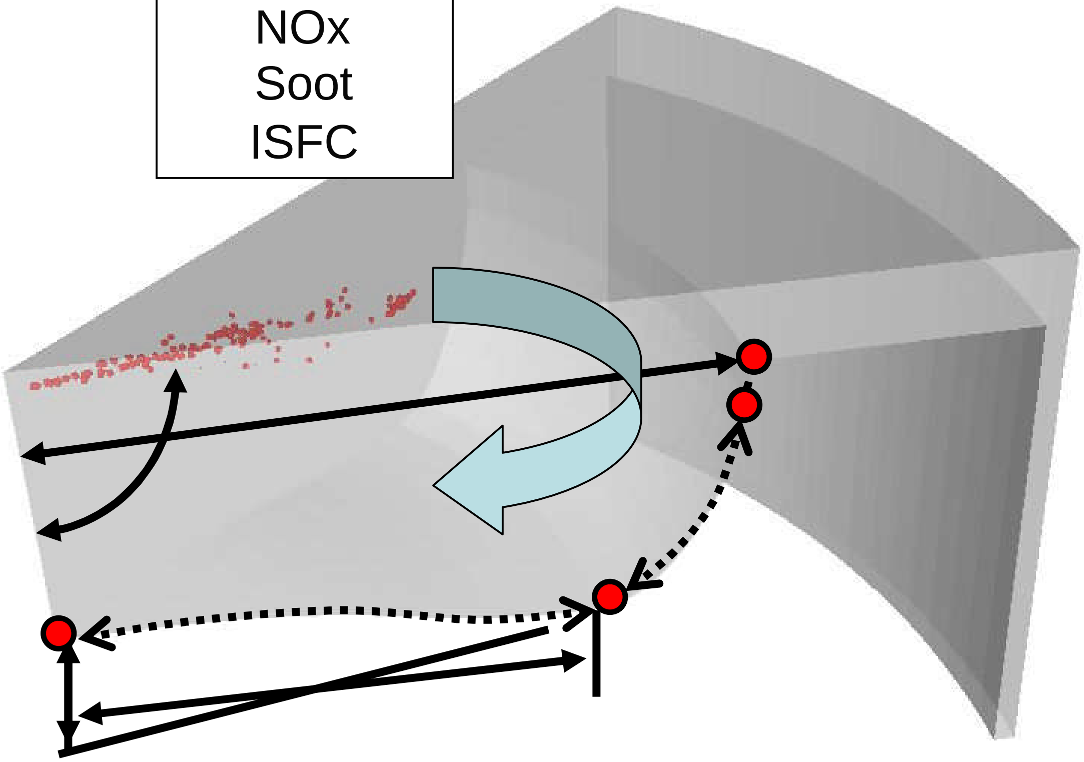
- Regression technique suitable for handling irregular and undesigned data sets (e.g., GA data) [2]
- Utilizes otherwise discarded optimization data
- Captures magnitude of effects AND the shape of their response

Liu, IJER 2006

Example Optimization - piston bowl design

Parameters and Objectives

Optimize:
NOx
Soot
ISFC



7 Geometry Parameters:

Pip height

Bowl diameter

ϕ of bowl bottom

4 curvature control points

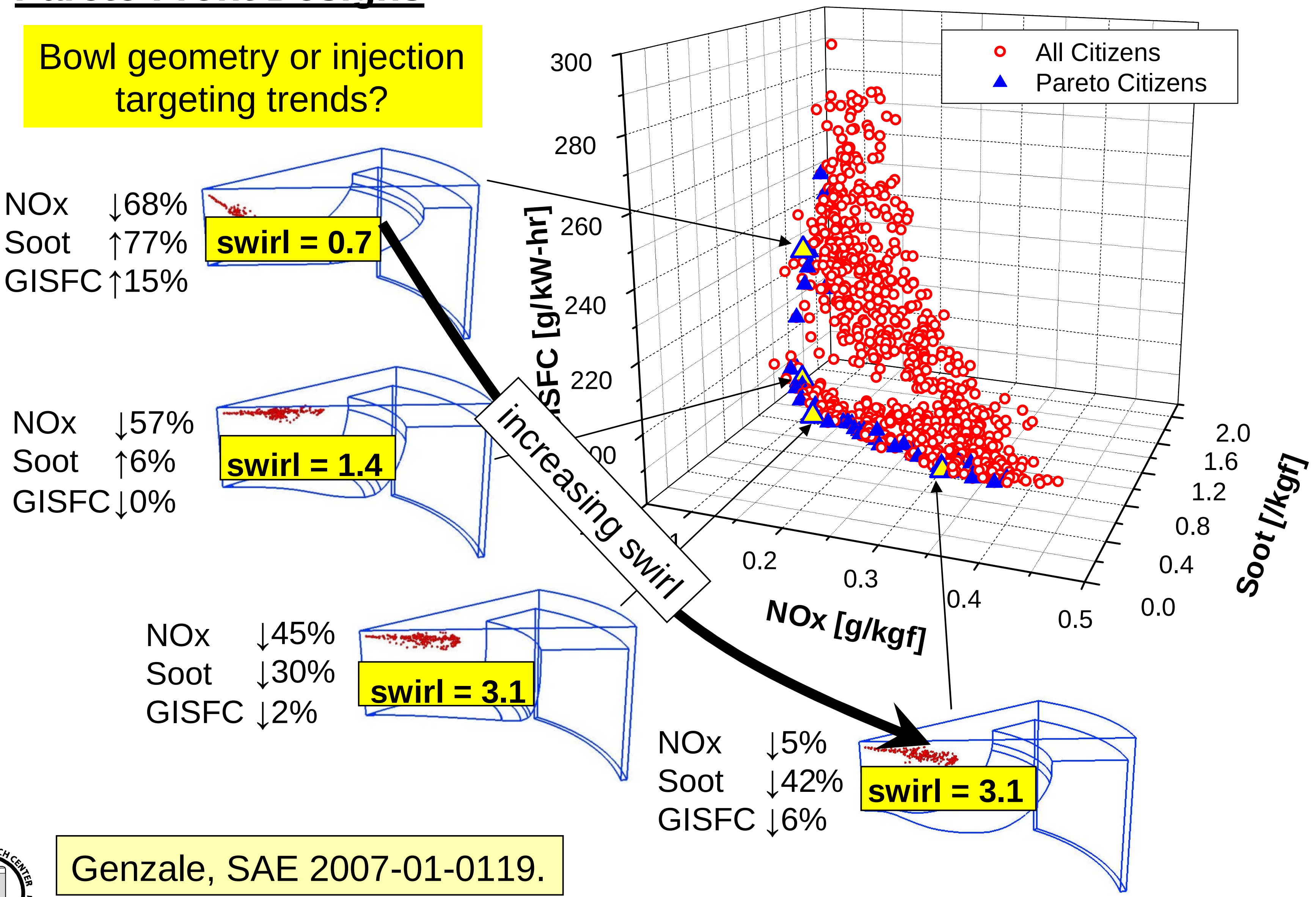
Injector Spray Angle

Swirl Ratio

Genzale, SAE 2007-01-0119.

Pareto Front Designs

Bowl geometry or injection targeting trends?



NOx ↓68%
Soot ↑77%
GISFC ↑15%

NOx ↓57%
Soot ↑6%
GISFC ↓0%

NOx ↓45%
Soot ↓30%
GISFC ↓2%

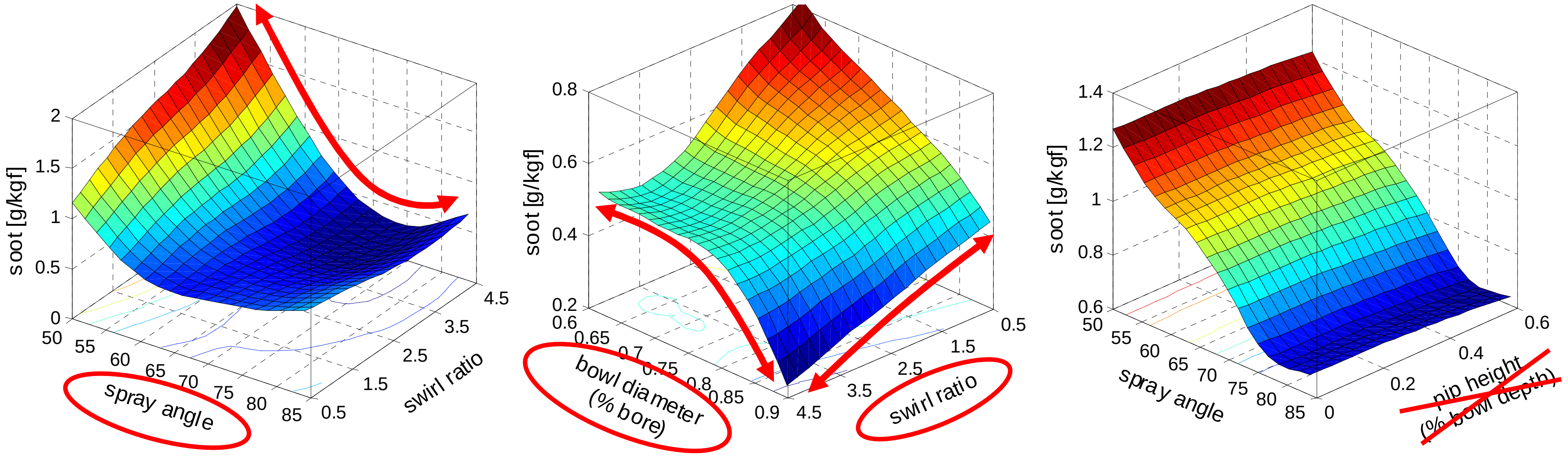
NOx ↓5%
Soot ↓42%
GISFC ↓6%

Genzale, SAE 2007-01-0119.

Regression – Used to Identify Dominant Design Parameters

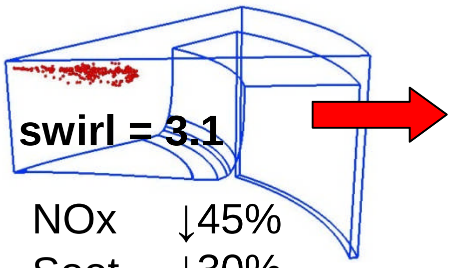
Regression fits performed for each design on the Pareto front

- 3 dominant design parameters identified:
  1. Spray angle
  2. Swirl ratio
  3. Bowl diameter

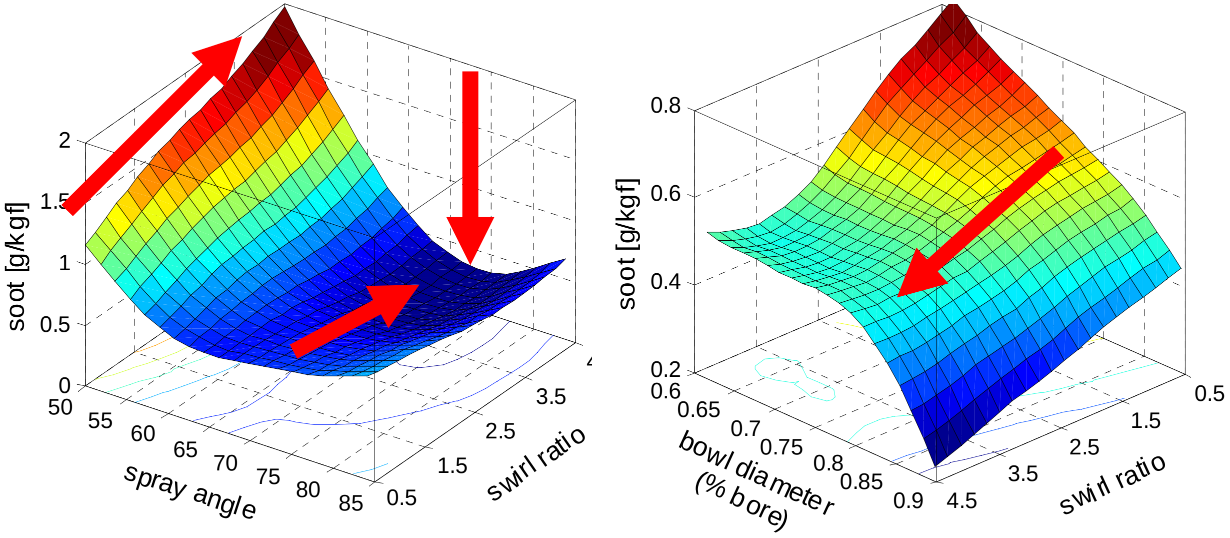


Genzale, SAE 2007-01-0119.

Regression – Used to Understand Parameter Effects



NOx ↓45%
Soot ↓30%
GISFC ↓2%



Response Surface Observations:

An optimal spray angle is predicted.

Increased swirl ratio is predicted to enhance soot reduction near the optimal spray angle.

<u>Increases</u> soot emissions at narrow spray angles.

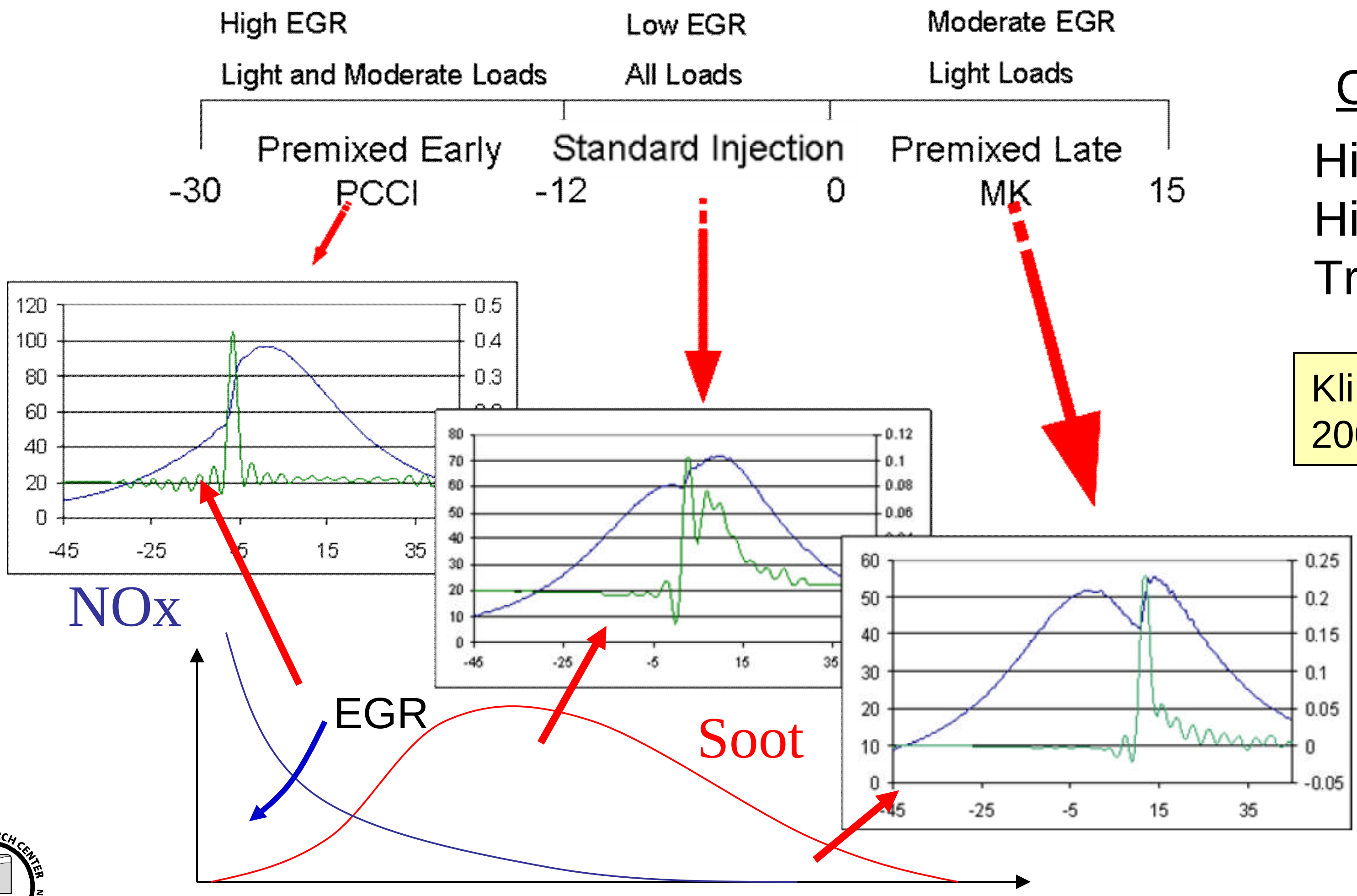
Increased swirl ratio is predicted to decrease soot at all bowl diameters.

Genzale, SAE 2007-01-0119.

Optimization of Low Temperature Combustion - LTC

Increased interest in new combustion regimes

HCCI, PCCI, MK - offers simultaneous reduction of NOx and soot



High EGR
Light and Moderate Loads

Low EGR
All Loads

Moderate EGR
Light Loads

Premixed Early
PCCI

Standard Injection

Premixed Late
MK

Challenges

High CO, HC
High loads
Transients

Klingbeil, SAE 2003-01-0341

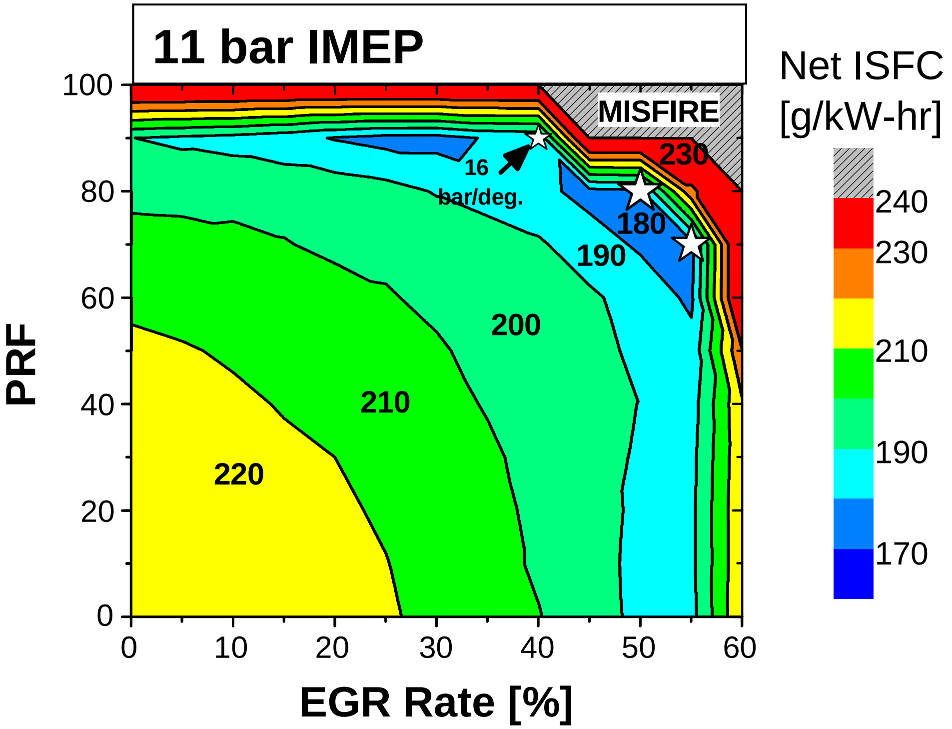
Combustion Optimization - Fuel and EGR Selection

HCCI simulations used to choose optimal EGR rate and PRF (isooctane/n-heptane) blend

- At 6, 9, and 11 bar IMEP
- 1300 rev/min

As load is increased the minimum ISFC **cannot** be achieved with either neat diesel fuel of neat gasoline

Predicted contours are in good agreement with HCCI experiments



Kokjohn, SAE 2009-01-2647

Hour 8: Optimization and Low Temperature Combustion

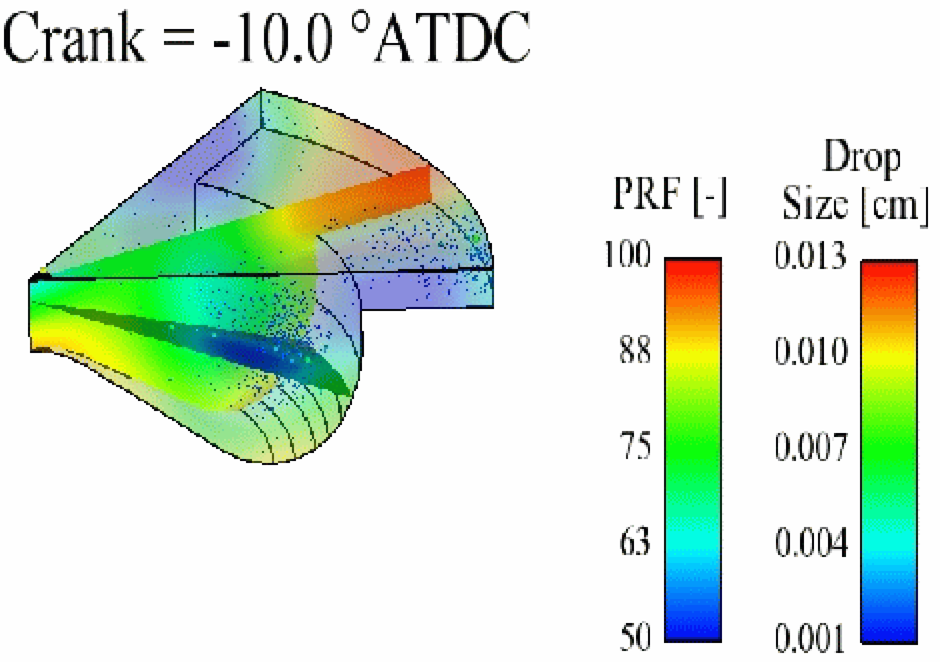
Charge preparation optimization

Premixed and Direct Injected fuel blending

- Desirable to use traditional diesel type injector
  - Large nozzle hole (250 μm)
  - Wide angle (145° included angle)

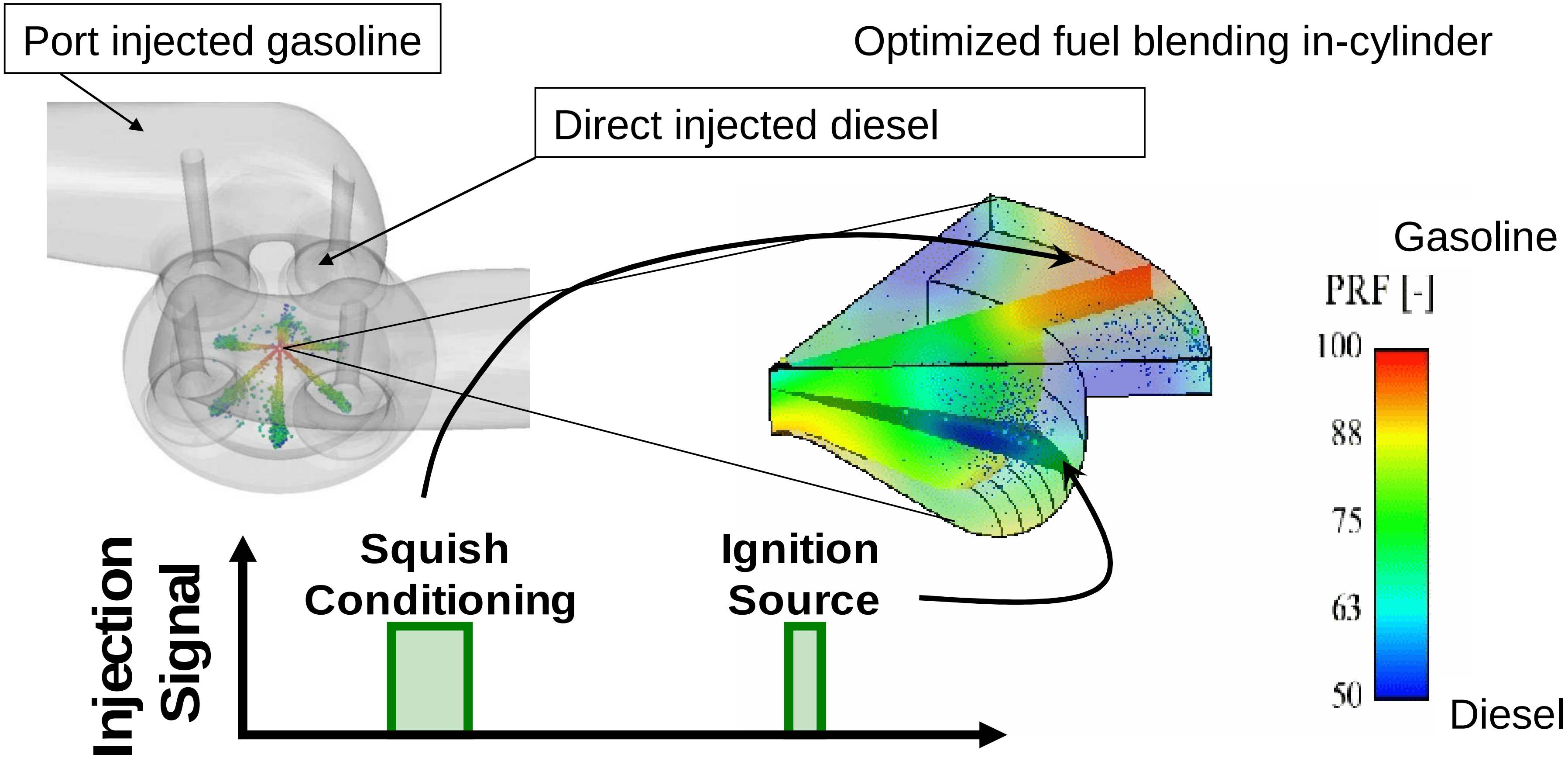
- KIVA + Multi-Objective Genetic Algorithm (MOGA)
- Fuel reactivity and EGR from HCCI investigation (9 bar IMEP)
  - Global PRF = 65
  - EGR rate = 50%
- Five optimization parameters
- Minimize two objectives
  - Wall film amount
  - PRF Inhomogeneity
- Simulations run to 10 °BTDC
- 21 generations with a population size of 24

Inj. 1 Pressure	100 to 1500 bar
Inj. 2 Pressure	100 to 1500 bar
SOI 1	IVC to (SOI2-20) ºATDC
SOI 2	-50 to -30 ºATDC



Kokjohn, SAE 2009-01-2647
Kokjohn & Reitz ICLASS 2009

Optimized Reactivity Controlled Compression Ignition (RCCI)



Port injected gasoline

Optimized fuel blending in-cylinder

Direct injected diesel

Gasoline

Diesel

Injection Signal

Squish Conditioning

Ignition Source

-80 to -50

-45 to -30

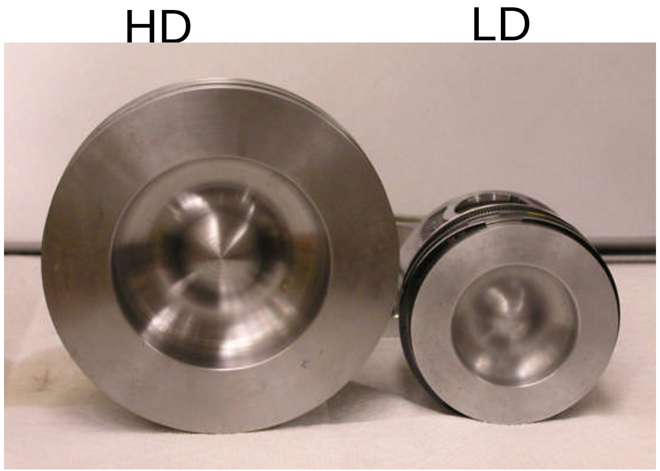
Crank Angle (deg. ATDC)

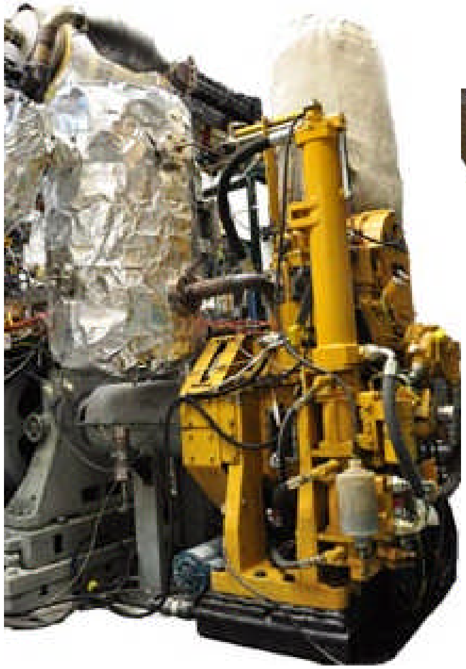
Gasoline Diesel

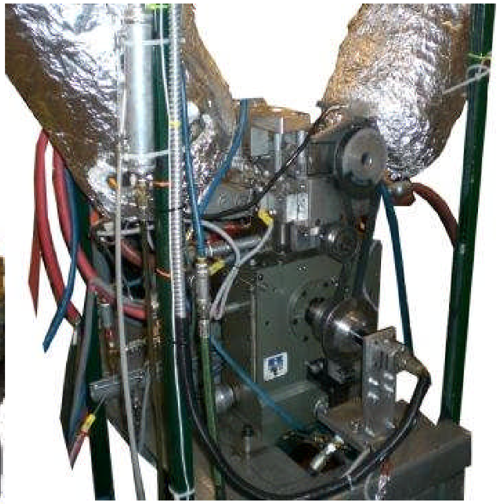
Kokjohn, SAE 2009-01-2647

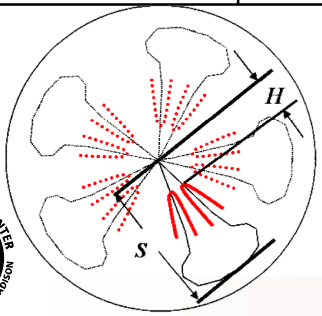
Heavy- and light-duty ERC experimental engines

Engine	Heavy Duty	Light Duty
Engine	CAT SCOTE	GM 1.9 L
Displ. (L/cyl)	2.44	0.477
Bore (cm)	13.72	8.2
Stroke (cm)	16.51	9.04
Squish (cm)	0.157	0.133
CR	16.1:1	15.2:1
Swirl ratio	0.7	2.2
IVC (° ATDC)	-85 and -143	-132
EVO(° ATDC)	130	112
Injector type	Common rail	
Nozzle holes	6	8
Hole size (µm)	250	128







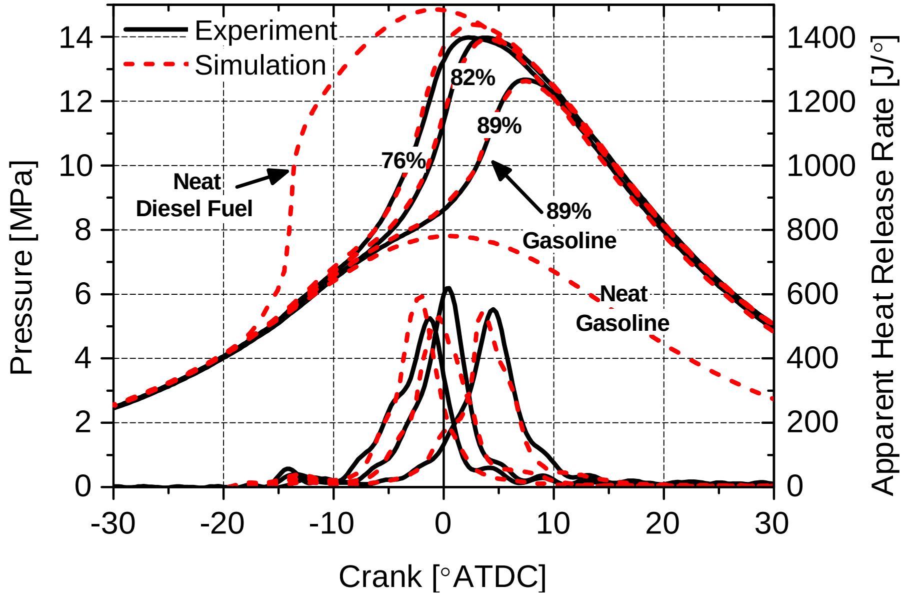


Engine size scaling
Staples, SAE
2009-01-1124

Experimental validation - HD Caterpillar SCOTE

IMEP (bar)	9		
Speed (rpm)	1300		
EGR (%)	43		
Equivalence ratio (-)	0.5		
Intake Temp. (° C)	32		
Intake pressure (bar)	1.74		
Gasoline (% mass)	76	82	89
Diesel inject press. (bar)	800		
SOI1 (° ATDC)	-58		
SOI2 (° ATDC)	-37		
Fract. diesel in 1st pulse	0.62		
IVC (ºBTDC)/Comp ratio	143/16		

Effect of gasoline percentage



Hanson, SAE 2010-01-0864

Computer modeling predictions confirmed

Combustion timing and Pressure Rise Rate control with diesel/gasoline ratio

Dual-fuel can be used to extend load limits of either pure diesel or gasoline

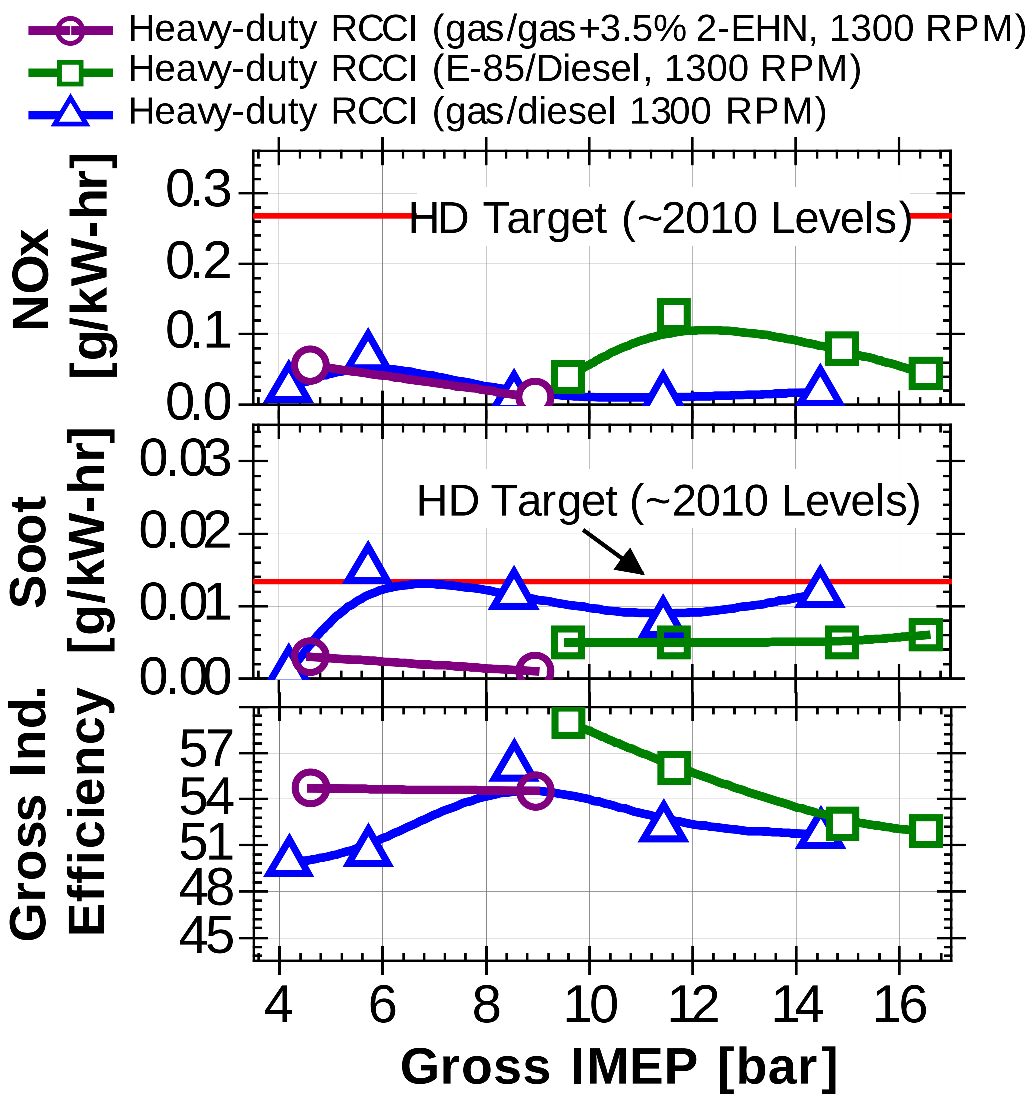
RCCI – high efficiency, low emissions, fuel flexibility

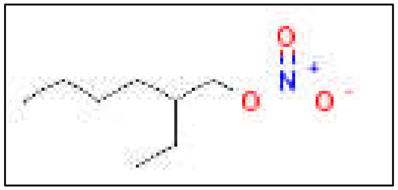
Indicated efficiency of 58±1% achieved with E85/diesel

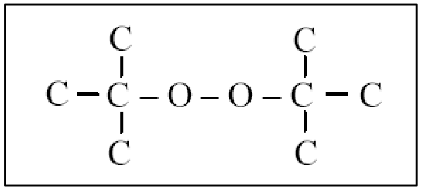
Emissions met in-cylinder, without need for after-treatment

Considerable fuel flexibility, including 'single' fuel operation

Diesel can be replaced with <0.5% total cetane improver (2-EHN/DTBP) in gasoline
- less additive than SCR DEF







Splitter, SAE 2010-01-2167; Hanson, SAE 2011-01-0361

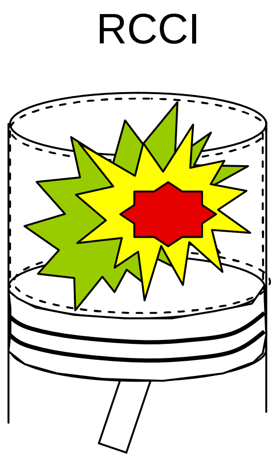
Dual fuel RCCI combustion – controlled HCCI

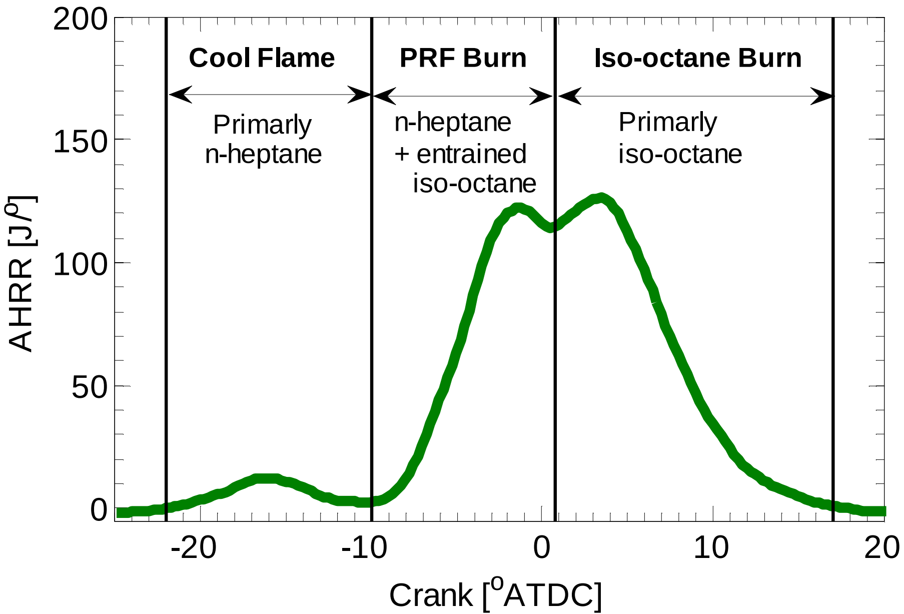
Heat release occurs in 3 stages (SAE 2010-01-0345, 2012-01-0375)

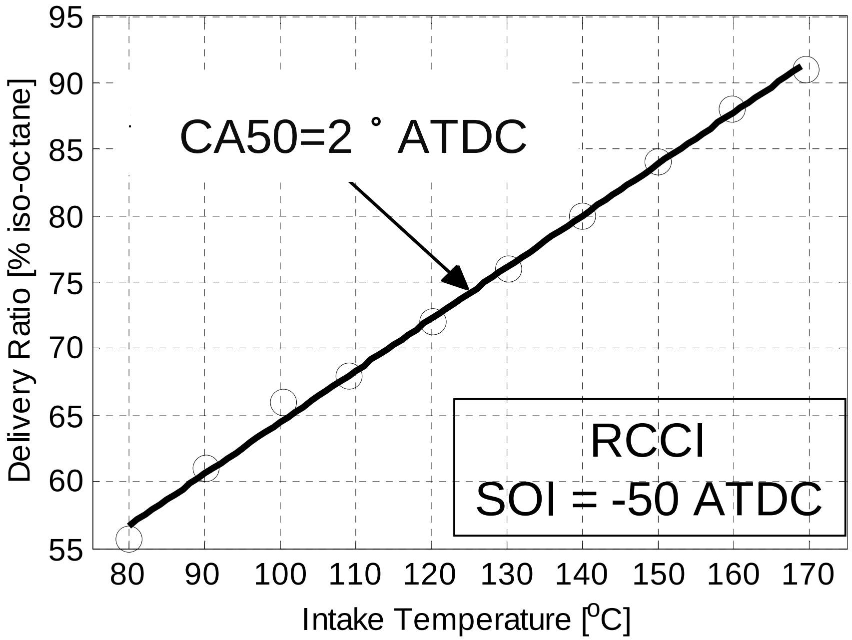
- Cool flame reactions result from diesel (n-heptane) injection
- First energy release occurs where both fuels are mixed
- Final energy release occurs where lower reactivity fuel is located

Changing fuel ratios changes relative magnitudes of stages

Fueling ratio provides “next cycle” CA50 transient control

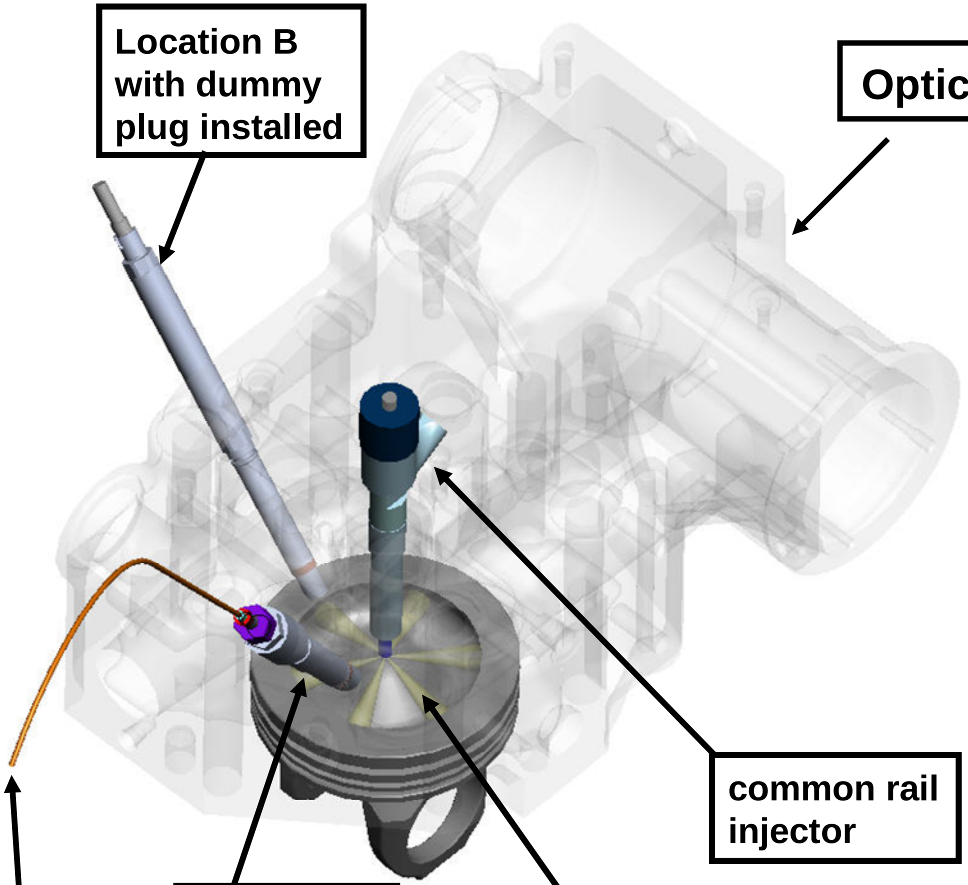






Kokjohn, IJER 2011

Understanding RCCI Combustion Process



Location B with dummy plug installed

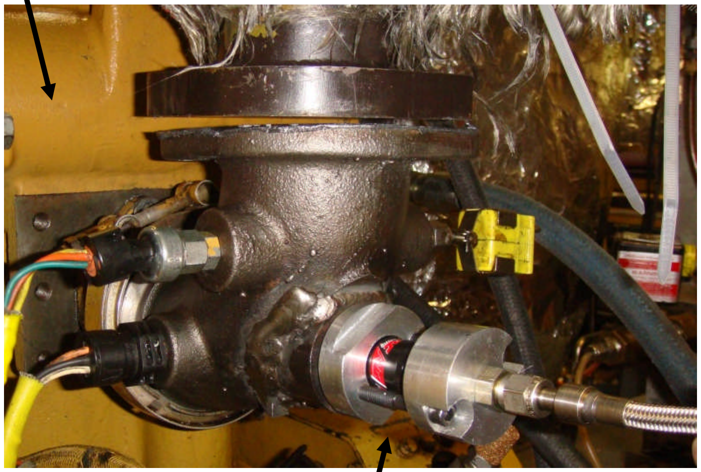
fiber to FTIR

Location A with optics installed

common rail fuel spray

common rail injector

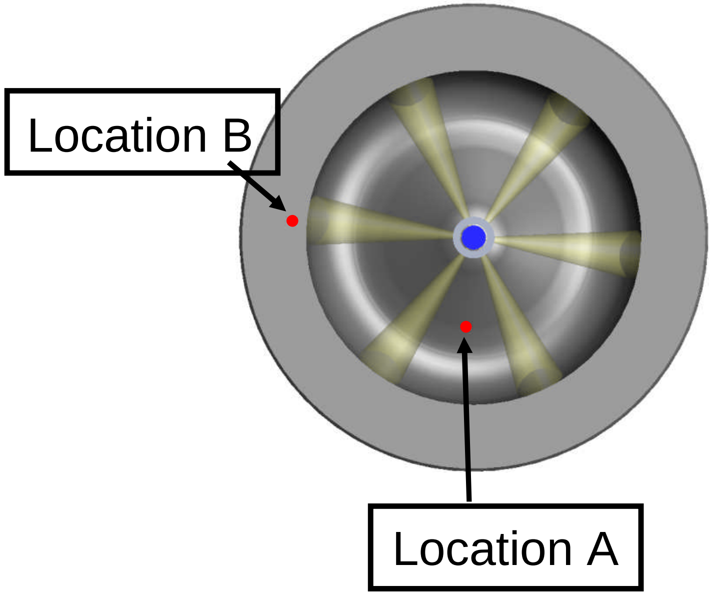
Optical Cylinder Head

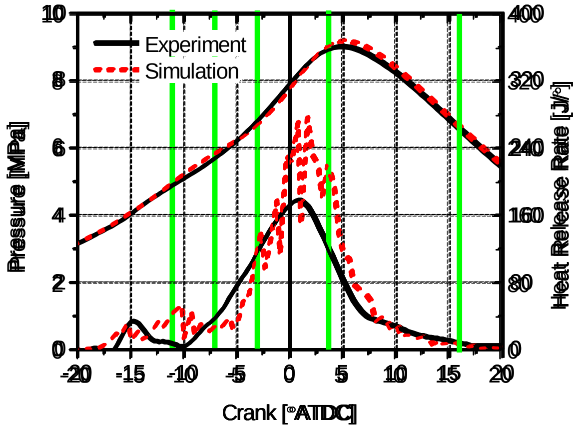


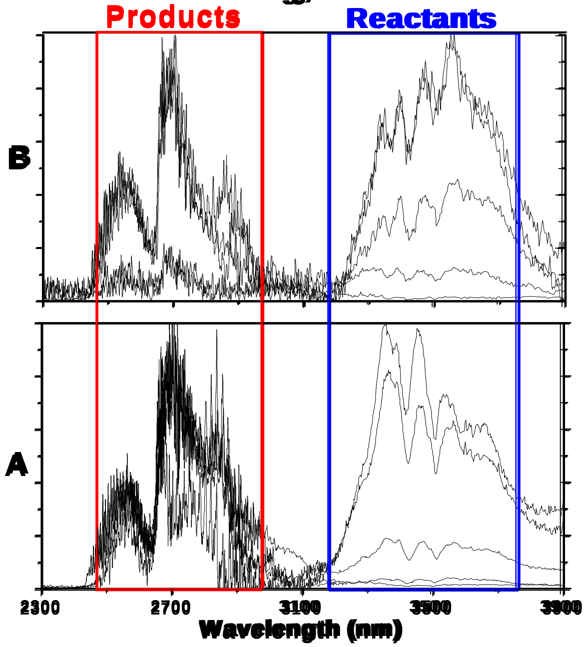
Port Fuel Injector

Splitter, SAE 2010-01-0345

Understanding RCCI Combustion Process







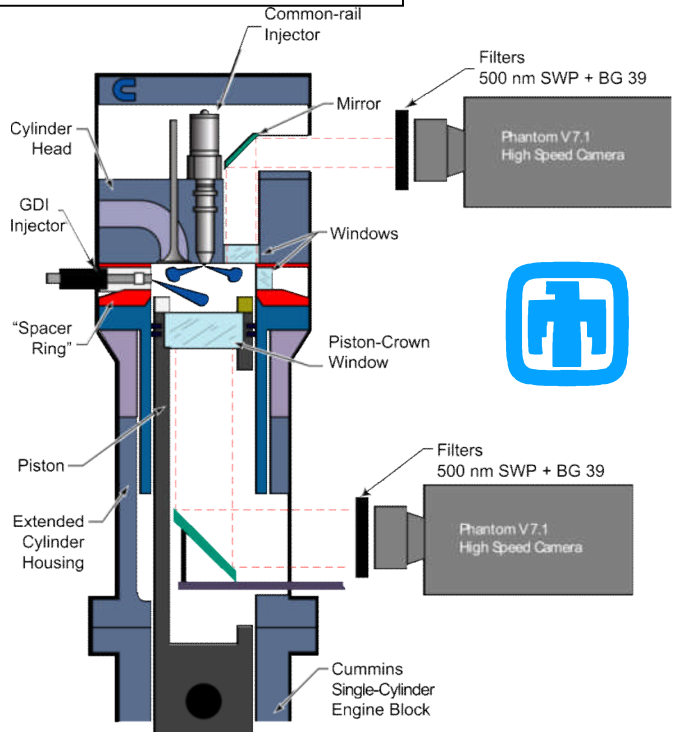
- Experimental in-cylinder FTIR measurements of combustion process at two locations
- Spectra shows different fuel species at locations A and B, a result of the reactivity gradient
- Fuel decomposition and combustion products form at a slower rate at location B, extending combustion duration

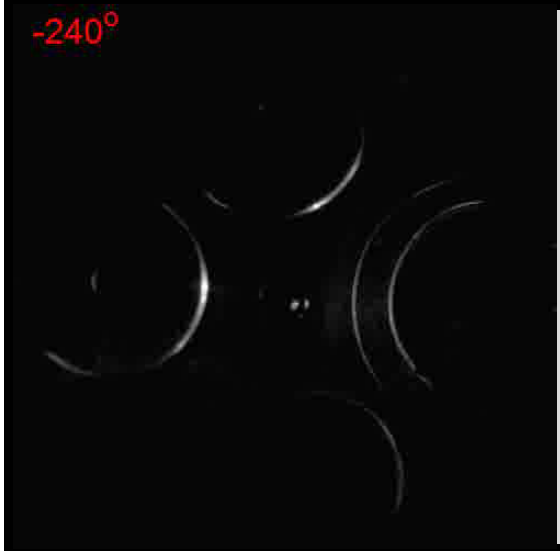
Splitter, SAE 2010-01-0345

RCCI optical experiments

Engine	Cummins N-14
Bore x stroke	13.97 x 15.24 cm
Displacement	2.34 L
Geometric compression ratio	10.75

- RCCI experiments in Sandia heavy-duty optical engine
- LED illumination through side windows to visualize sprays
- Images recorded through both piston-crown and upper window
- Crank-angle-resolved high-temperature chemiluminescence with high-speed CMOS camera
- Short-wave pass filter to reject long-wavelength (green through IR) soot luminosity





GDI
Iso-octane
100 bar
7x150 micron

Common-rail
n-heptane
600 bar
8x140 micron
Inc. Ang. 152°

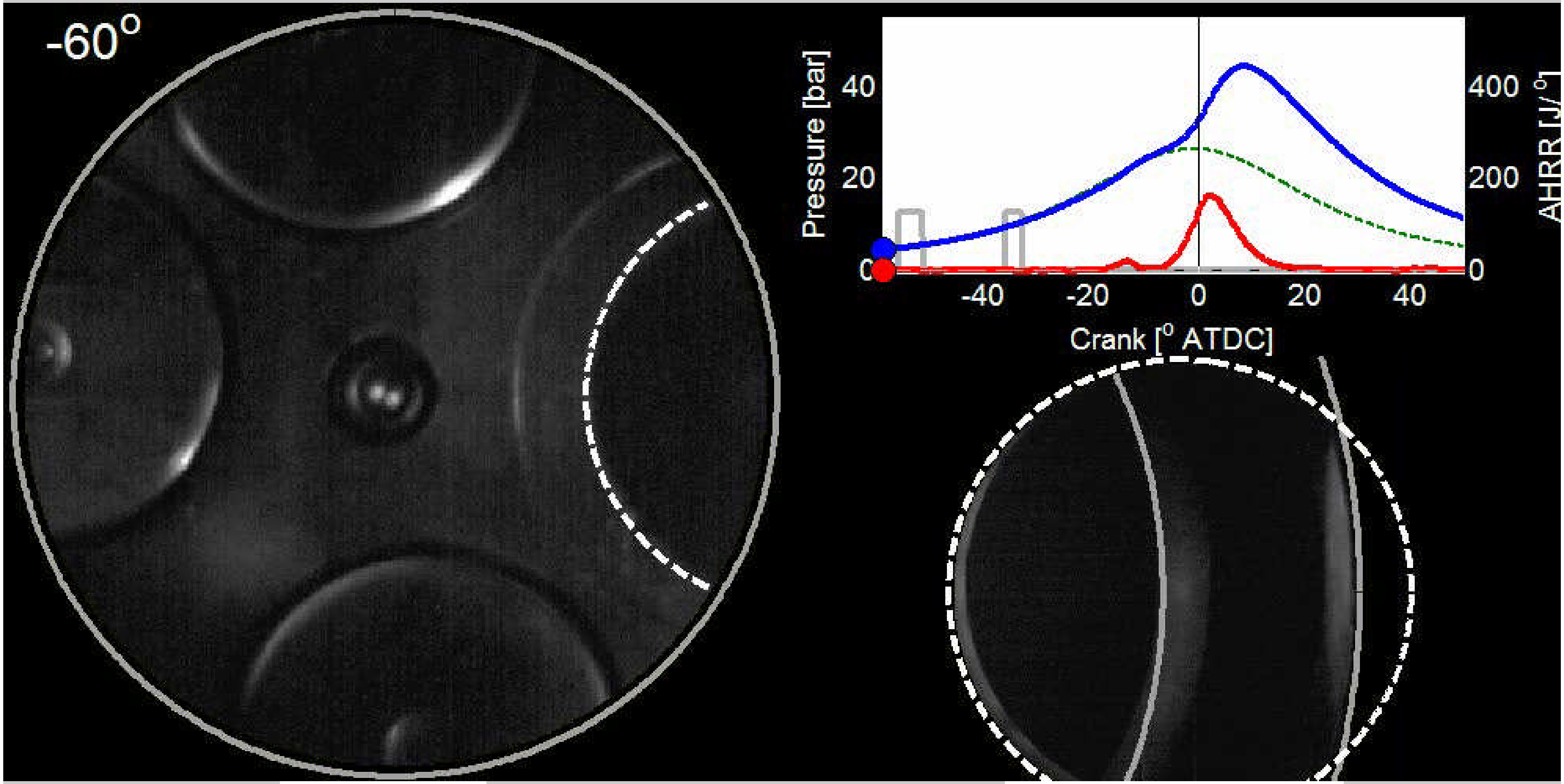
Kokjohn, SAE 2012-01-0375

RCCI combustion luminosity imaging

Load: 4.2 bar IMEP
Speed: 1200 rpm
Intake Temperature: 90° C
Intake Pressure: 1.1 bar abs.

Kokjohn, ILASS-2011

GDI SOI: -240°ATDC
CR SOI: -57°/-37° ATDC
Equivalence ratio: 0.42
Iso-octane mass %: 64



Bowl window

Squish (upper) window

Comparison of dual fuel RCCI and single fuel LTC

Kokjohn, A&S 2011

Engine specifications

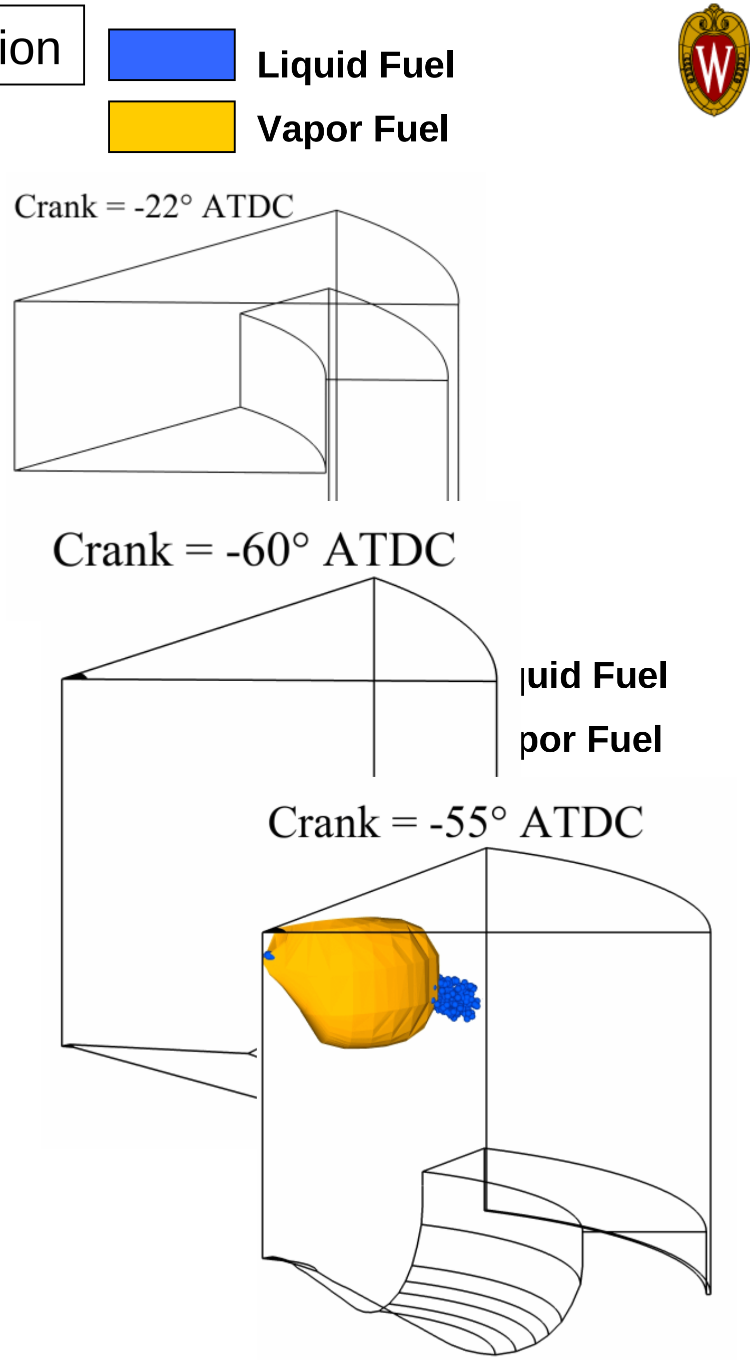
Three engines operating with different forms of LTC combustion

Case	Diesel LTC[1]	Ethanol PPCI[2]	Dual-Fuel RCCI[3]
Engine	Cummins N14	Scania D12	CAT 3401
Displacement (cm3)	2340	1966	2440
Stroke (mm)	152.4	154	165.1
Bore (mm)	139.7	127.5	137.2
Con. Rod (mm)	304.8	255	261
CR (-)	11.2	14.3:1	16.1
Swirl Ratio (-)	0.5	2.9	0.7
Number of nozzles	8	8	6
Nozzle hole size (μm)	196	180	250

1. Singh, CNF 2009
2. Manente, SAE 2010-01-0871
3. D. A. Splitter, THIESEL 2010

Comparison with single fuel LTC

- Diesel LTC
  - Single early injection at 22° BTDC
  - 1600 bar injection pressure
  - Diluted intake (~60% EGR)
- Ethanol PPCI
  - Single early injection at 60° BTDC
  - 1800 bar injection pressure
  - No EGR
- Dual-fuel RCCI
  - Port-fuel-injection of low reactivity fuel (gasoline or E85)
  - Direct-injection of diesel fuel
  - Split early injections (SOI1 = 58° BTDC and SOI2 = 37° BTDC)
  - 800 bar injection pressure



Kokjohn, A&S 2011

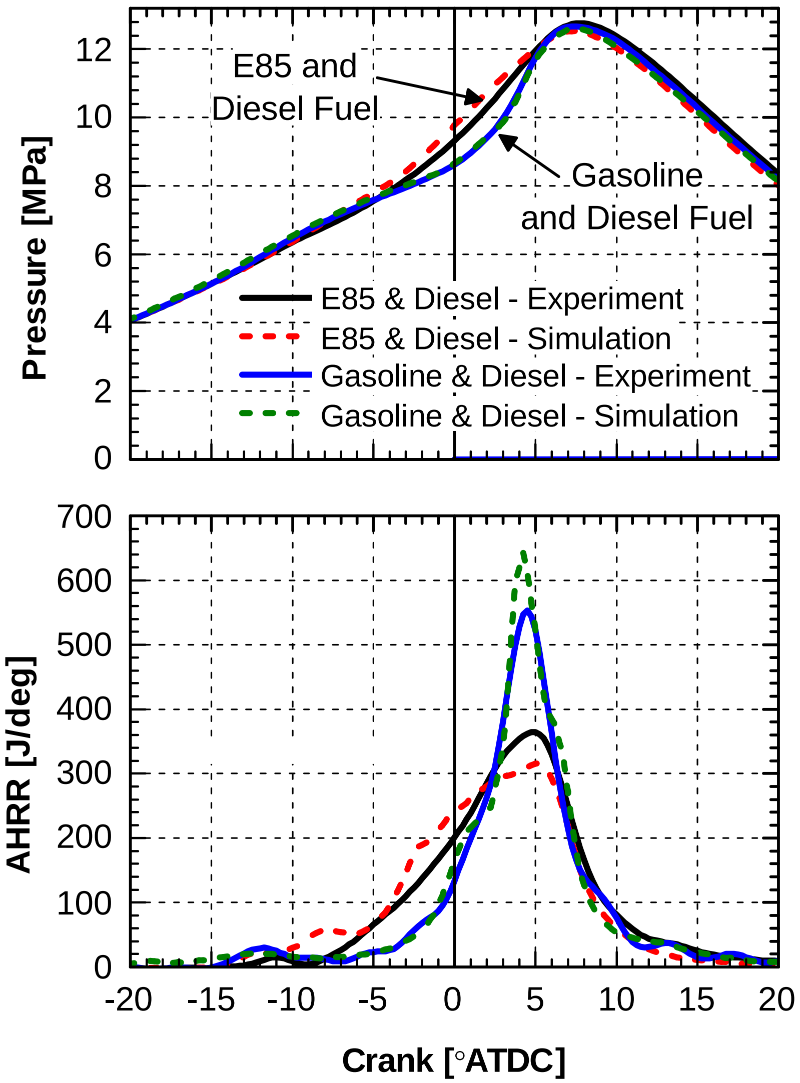
Dual-fuel RCCI

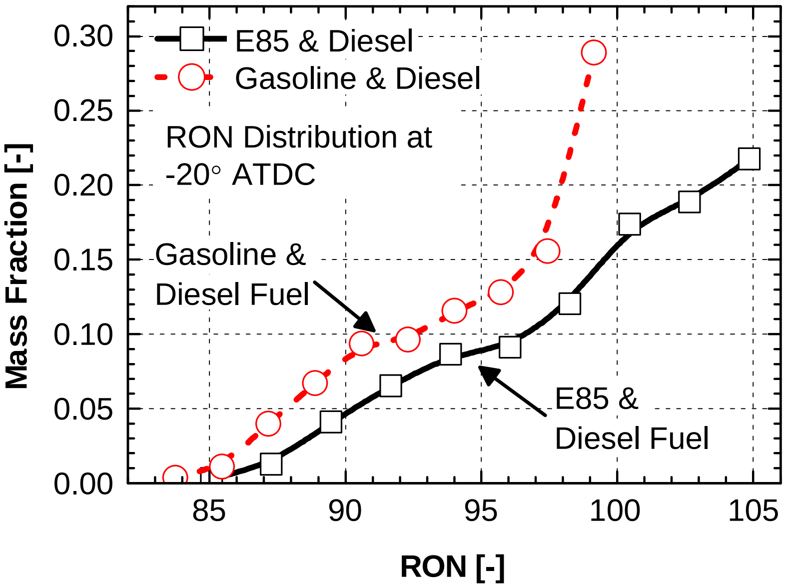
Comparison of gasoline-diesel and E85-diesel dual-fuel RCCI combustion

For fixed combustion phasing, E85-diesel DF RCCI exhibits significantly reduced RoHR (and therefore peak PRR) compared to gasoline-diesel RCCI allows higher load operation

E85-diesel RCCI combustion has larger spread between most reactive (lowest RON) and least reactive (highest RON)

Kokjohn, A&S 2011





Comparison between diesel LTC, ethanol PPCI, and RCCI

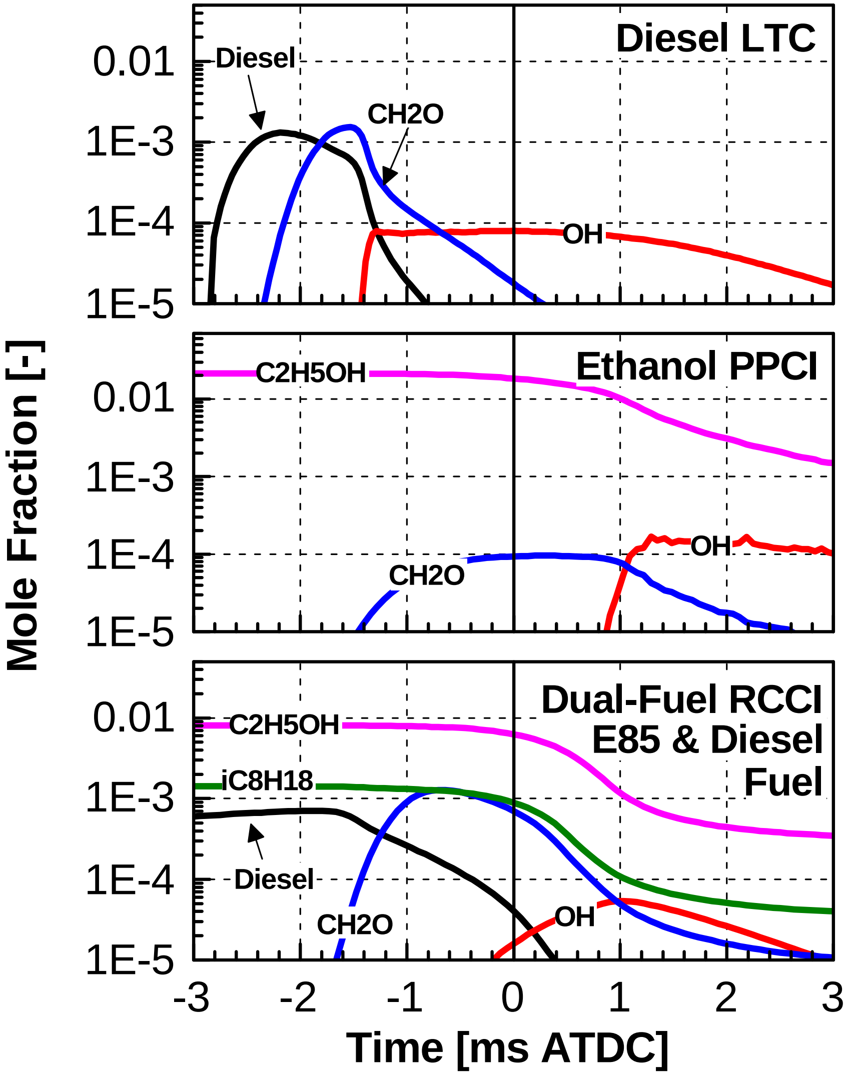
Evolution of key intermediates:

Reaction progress

$$\text{fuel} \rightarrow \underbrace{CH_2O}_{\substack{\text{first stage}\\ \text{combustion}}} \rightarrow \underbrace{OH}_{\substack{\text{second stage}\\ \text{combustion}}}$$

E85-diesel RCCI combustion shows a staged consumption of more reactive diesel fuel and less reactive E85

Ethanol and gasoline are not consumed until diesel fuel transitions to second stage ignition

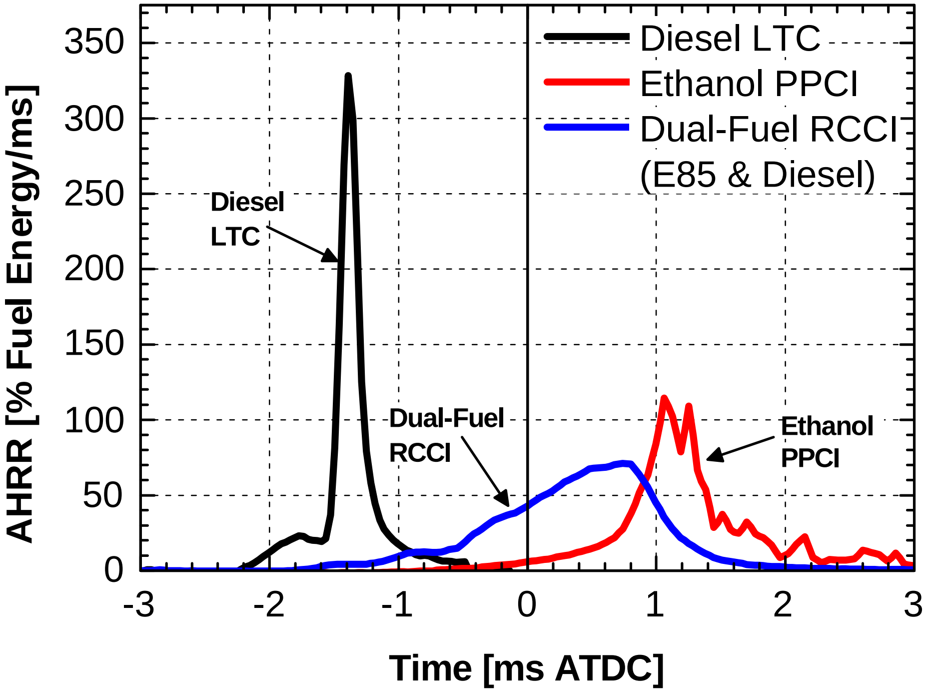


Kokjohn, A&S 2011

Comparison between diesel LTC, ethanol PPCI, and RCCI

- Diesel LTC
  - Earliest combustion phasing and most rapid energy release rate
  - High reactivity of diesel fuel requires significant charge dilution to maintain appropriate combustion phasing (12.7% Inlet O_2)
- Ethanol PPCI
  - Low fuel reactivity and charge cooling results in delayed combustion
  - Sequential combustion from lean-high temperature regions to rich-cool regions results in extended combustion duration
- Dual fuel RCCI
  - Combustion begins only slightly later than diesel LTC
  - Combustion duration is broad due to spatial gradient in fuel reactivity
  - Allows highest load operation due to gradual transition from first- to second-stage ignition

Kokjohn, A&S 2011



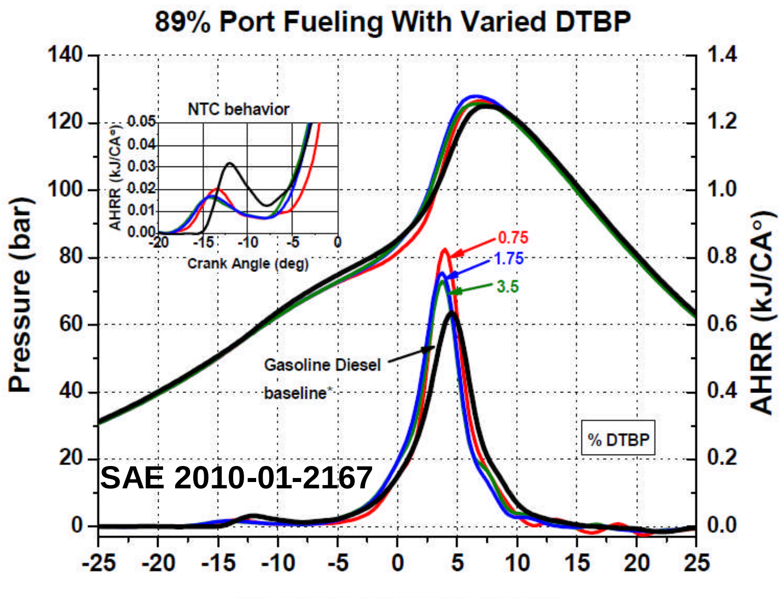
RCCI Engine Experiments
Hanson SAE 2010-01-0864
Kokjohn IJER 2011
Kokjohn SAE 2011-01-0357

‘Single fuel’ RCCI

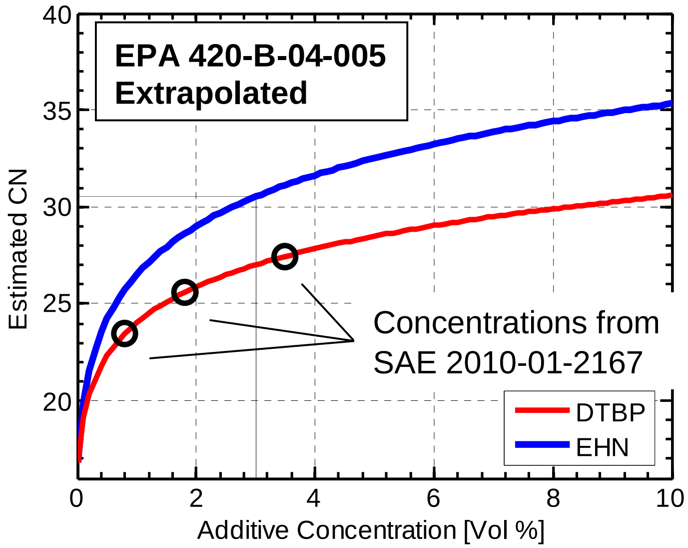
- RCCI is inherently fuel flexible and is promising to control PCI combustion. Can similar results be achieved with a single fuel and an additive?
- Splitter et al. (SAE 2010-01-2167) demonstrated single fuel RCCI in a heavy-duty engine using gasoline + Di-tertiary-Butyl Peroxide (DTBP)

- 2-Ethylhexyl Nitrate (EHN) is another common cetane improver
  - Contains fuel-bound NO and LTC results have shown increased engine-out NOx

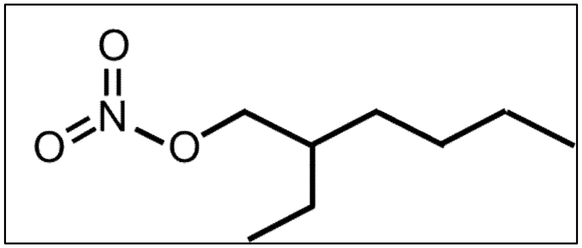
    (Ickes et al. Energy and Fuels 2009)



* data from Hanson et al. [4]



Concentrations from SAE 2010-01-2167



Kaddatz SAE 2012-01-1110

Comparison of E10-EHN and Diesel Fuel

Engine experiments performed on ERC GM 1.9L engine

Diesel fuel and splash blended E10-3% EHN mixtures compared under conventional diesel conditions (5.5 bar IMEP, 1900 rev/min)

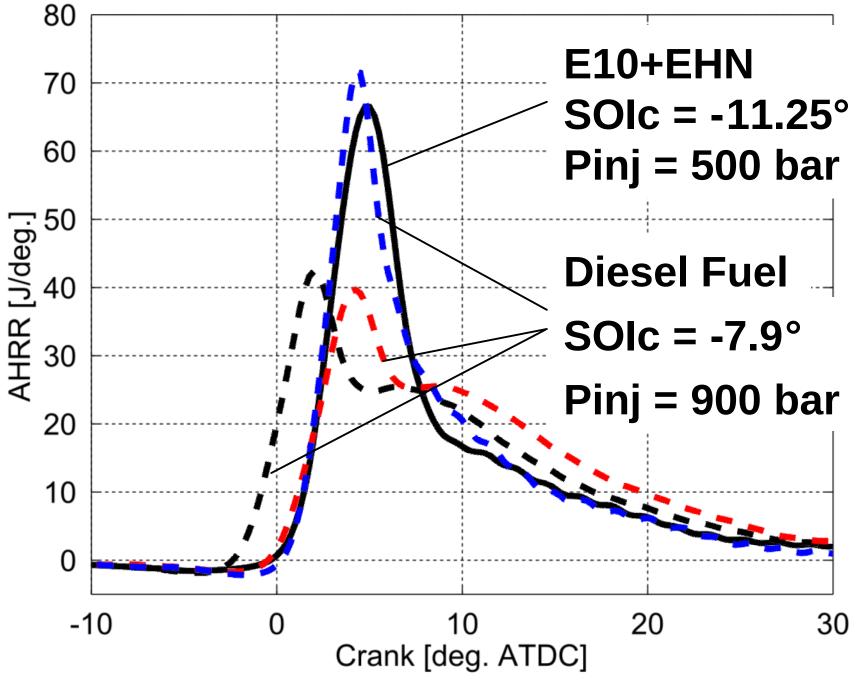
- Diesel fuel injection parameters adjusted to reproduce combustion characteristics of E10+EHN blend

Ignition Differences

- Diesel fuel SOI must be retarded to match ign. (Consistent with lower CN)

Mixing Differences

- Diesel fuel injection pressure must be increased by 400 bar to reproduce premixed burn



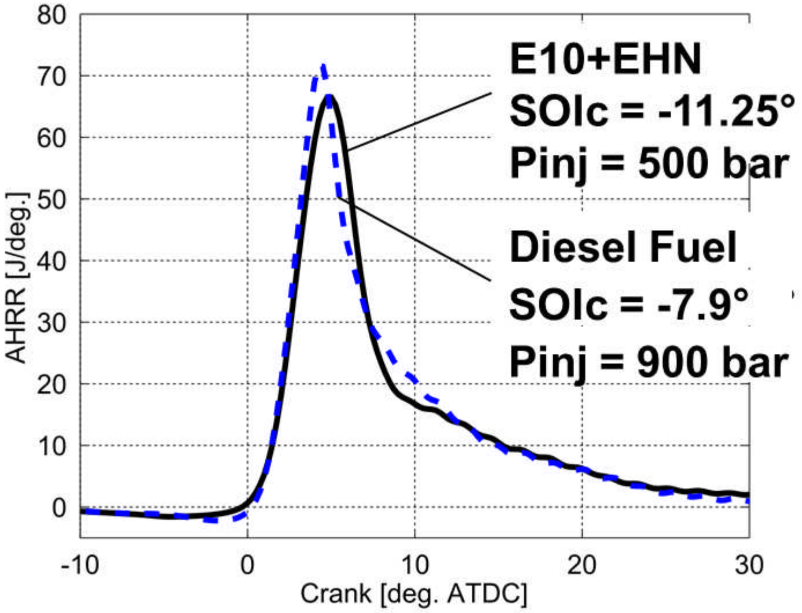
Diesel Fuel

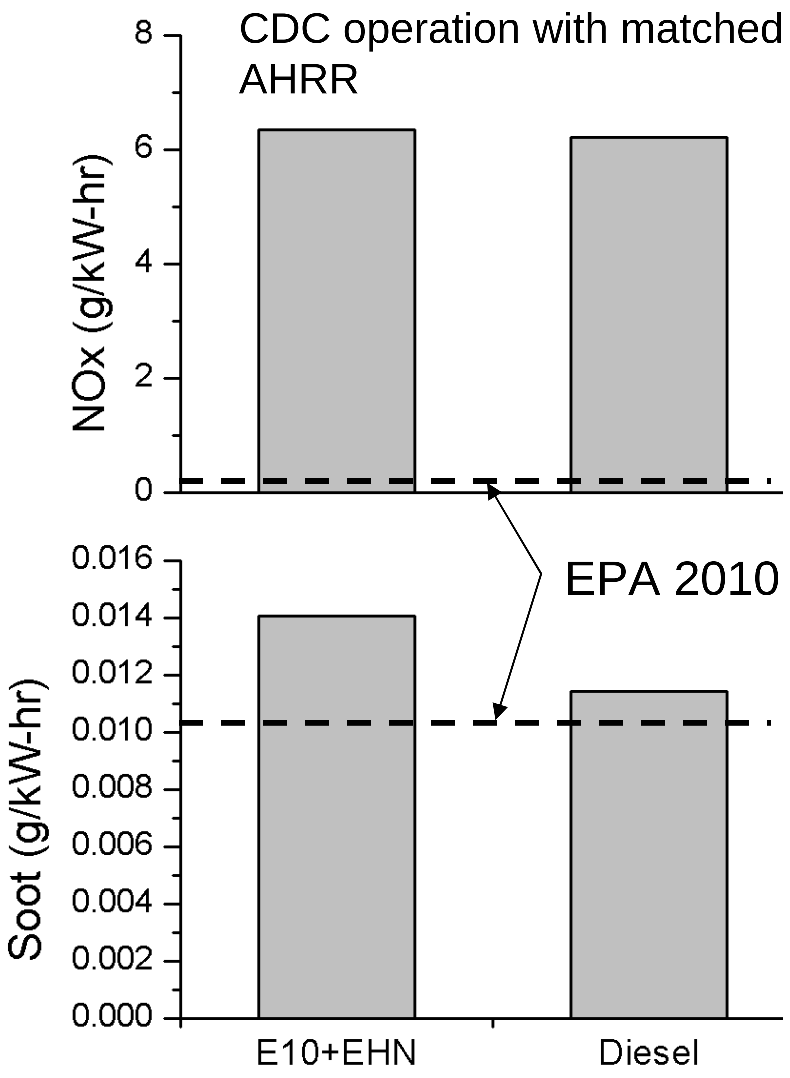
SOIc = -11.5	**Pinj = 500 bar**
SOIc = -9.25	**Pinj = 500 bar**
SOIc = -7.9	**Pinj = 900 bar**

Kaddatz SAE 2012-01-1110

Comparison of E10-EHN and Diesel Fuel

- Diesel fuel and E10-EHN compared under conventional diesel conditions (5.5 bar IMEP, 1900 rev/min)
  - Diesel fuel injection parameters adjusted to reproduce combustion characteristics of E10+EHN blend
- For CDC operation, E10+EHN and diesel fuel show similar NOx and soot

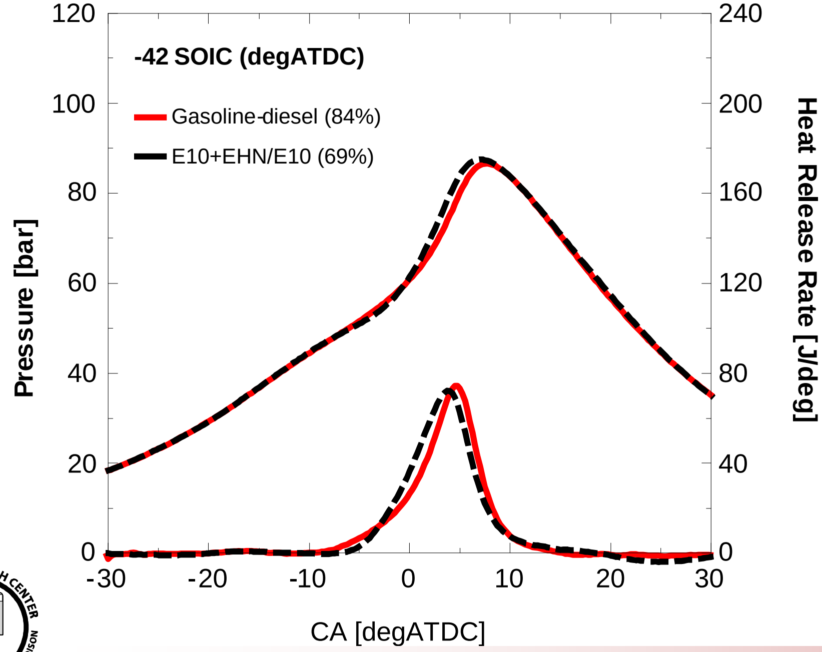



CDC operation with matched AHRR

Kaddatz SAE 2012-01-1110

Diesel/Gasoline and E10+EHN RCCI

- PFI E10 and direct-injected E10+3% EHN compared to gasoline – diesel RCCI operation
- Combustion characteristics of gasoline-diesel RCCI reproduced with E10 – E10+3%EHN
  - Adjustment to PFI percentage required to account for differences in ignitability



Operating Conditions

DI Fuel	E10+EHN	Diesel
PFI Fuel	E10	Gasoline
Net IMEP (bar)	5.5	
Engine Speed (RPM)	1900	
Premixed Fuel (% mass)	69	84
Common Rail SOIc(°ATDC)	-32 to -52	
Injection Pressure (bar)	500	800
Intake Temperature (C)	65	
Boost Pressure (bar)	1.3	
Swirl Ratio	1.5	
EGR (%)	0	

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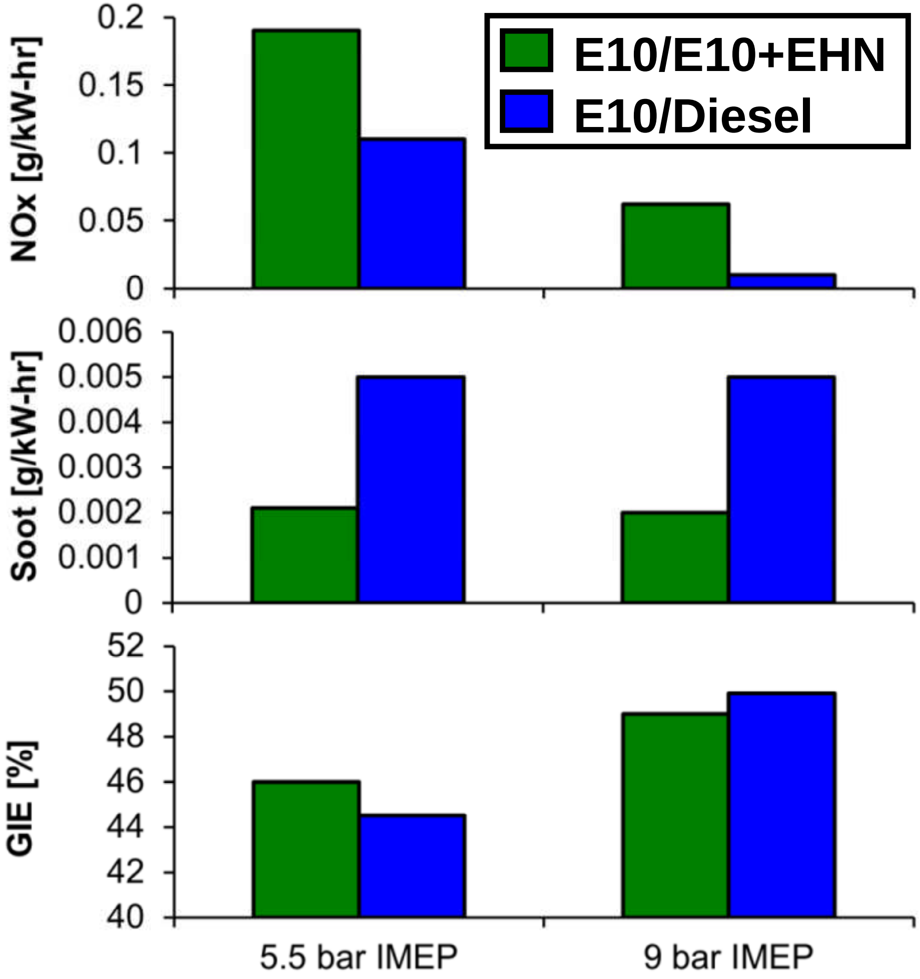
Performance of E10 and E10+EHN RCCI

Parametric studies performed to optimize efficiency of single-fuel RCCI at 5.5 and 9 bar IMEP

Using a split-injection strategy, performance characteristics of single-fuel + additive RCCI are similar to those of dual-fuel RCCI

Peak efficiency data for E10/E10+EHN shows higher NOx emissions, but levels meet EPA mandates

Soot is very low for all cases



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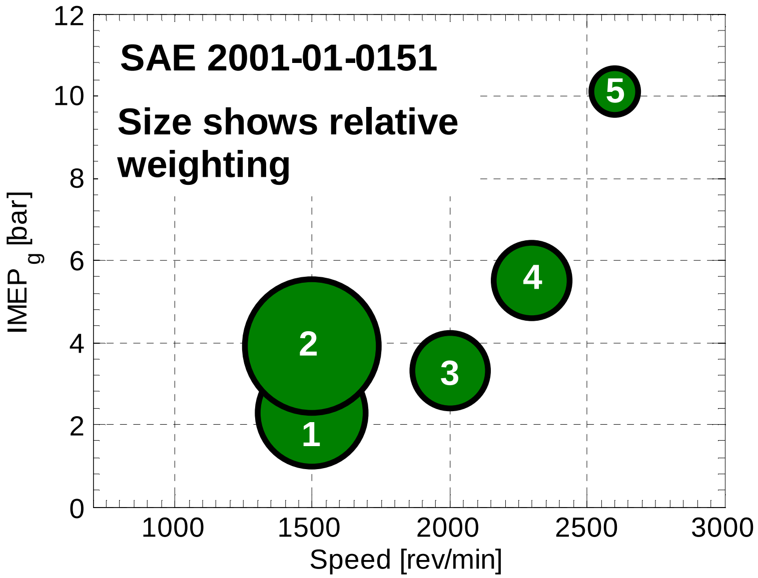
Additive Consumption Estimate

Light-duty drive cycle average is 55% PFI fuel (i.e., 45% additized fuel)

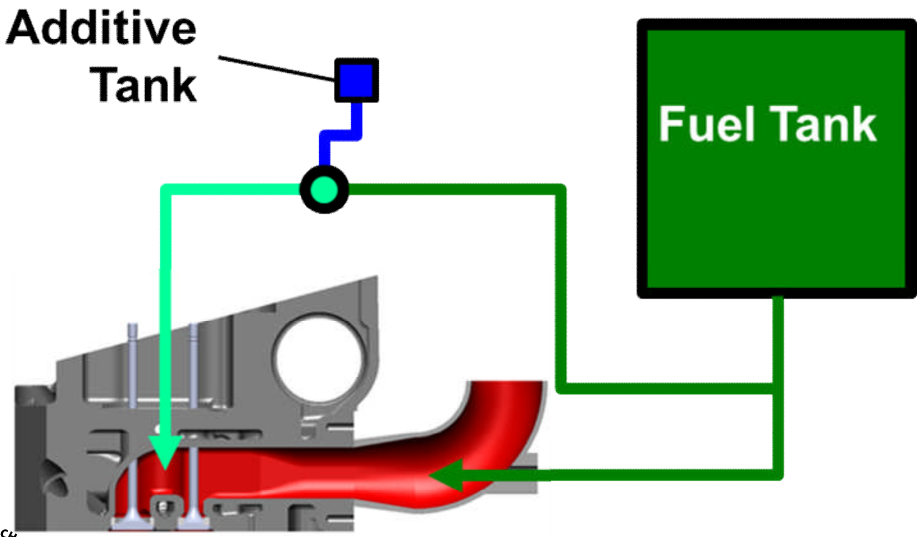
3% additive level → EHN volume is ~1.4% of the total fuel volume

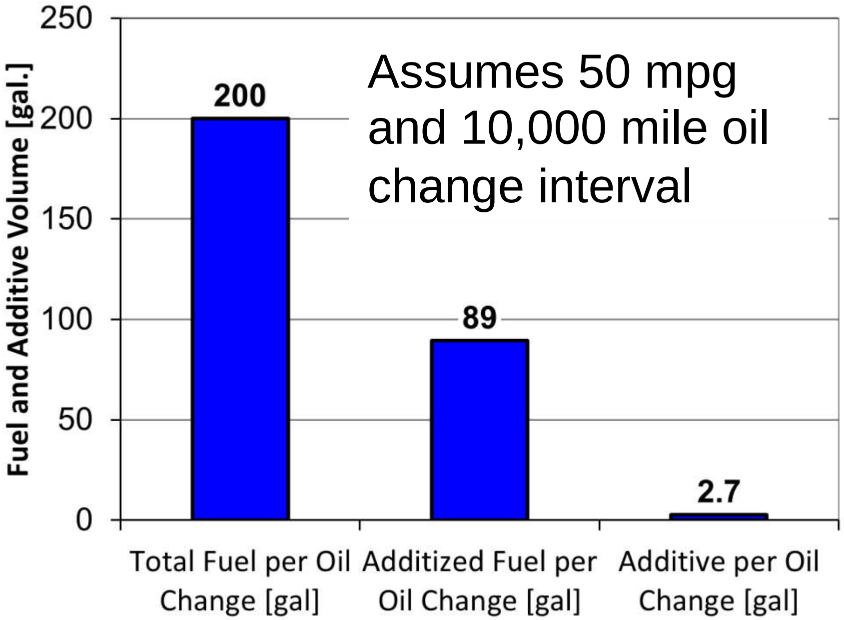
Similar to DEF levels

Assuming 50 mpg and 10,000 mile oil change intervals, additive tank must be ~2.7 gallons


SAE 2001-01-0151

Size shows relative weighting




Assumes 50 mpg and 10,000 mile oil change interval

Summary and Conclusions

CFD modeling can be integrated with efficient optimization techniques for improved engine design

New combustion strategies can be discovered using CFD-optimization

Reactivity Controlled Compression Ignition strategy explained and validated with engine experiments

Dual fuel and single-fuel (with additive) RCCI demonstrated to provide combustion control using optimized blending of port- and direct-injected fuels

RCCI offers high thermal efficiency and meets EPA NOx and soot emissions mandates in-cylinder, without the need for after-treatment