Internal Combustion Engines
I: Fundamentals and Performance Metrics

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2018 Princeton-Combustion Institute
Summer School on Combustion
Course Length: 9 hrs

(Mon.- Wed., June 25-27)

Short course outline:

Internal Combustion (IC) 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, Thermodynamics and 0-D modeling
Hour 2: 1-D modeling, Charge Preparation
Hour 3: Engine Performance Metrics, 3-D flow modeling

Day 2 (Computer modeling/engine processes)

Hour 4: Engine combustion physics and chemistry
Hour 5: Premixed Charge Spark-ignited engines
Hour 6: Spray modeling

Day 3 (Engine Applications and Optimization)

Hour 7: Heat transfer and Spray Combustion Research
Hour 8: Diesel Combustion modeling
Hour 9: Optimization and Low Temperature Combustion

Overview of optimization techniques

- Enumerative or exhaustive
- Calculus or gradient-based

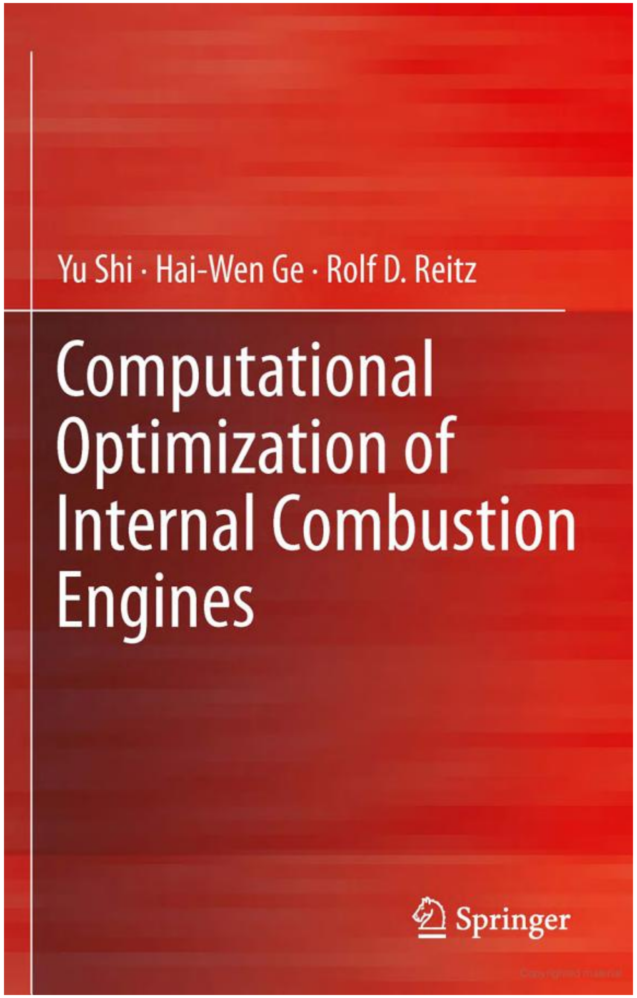
  "local" methods which search in the neighborhood of current design point
- Random

  "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



Senecal, 2000

Genetic algorithms

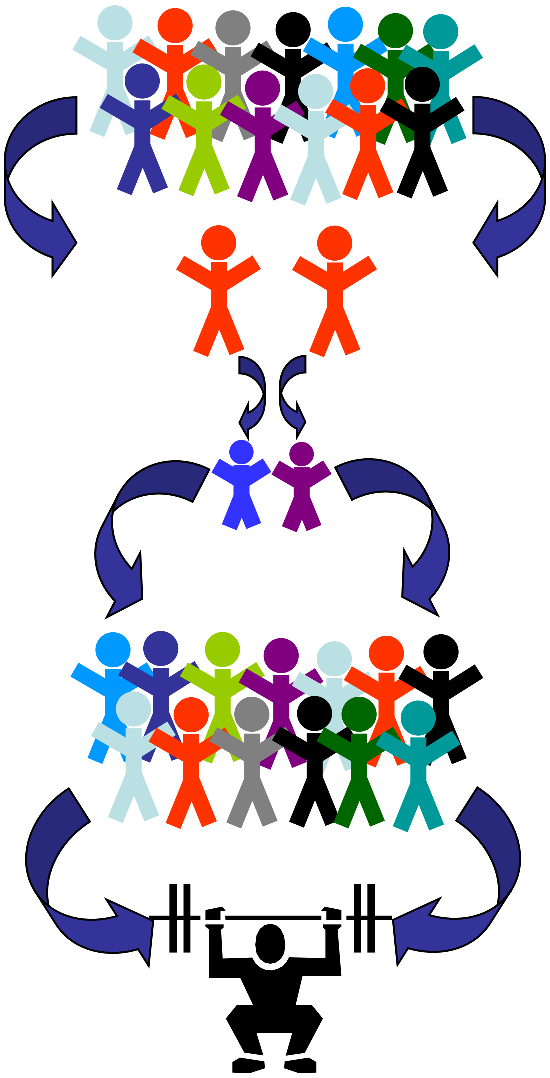
"Individuals" are generated through random selection and a "population" is produced

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



Implementation of algorithm

Goldberg, 1989
Carrol, 1996
Senecal, 2000

Binary representation of parameters X - "genes"

X_1	X_2	X_3
10101101	01101	01001001

- "chromosome" gene string

λ

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

Evaluate merit *f* (X) for each generation member - identify "fittest" members
Binary tournament selection → Bit-swapping "Cross-over"

Parent 1

10101101 01101010010001

Parent 2

01100100 11101101011011

10101101 11101101011011

01100100 01101010010001

Bit-flipping
Random "mutation"

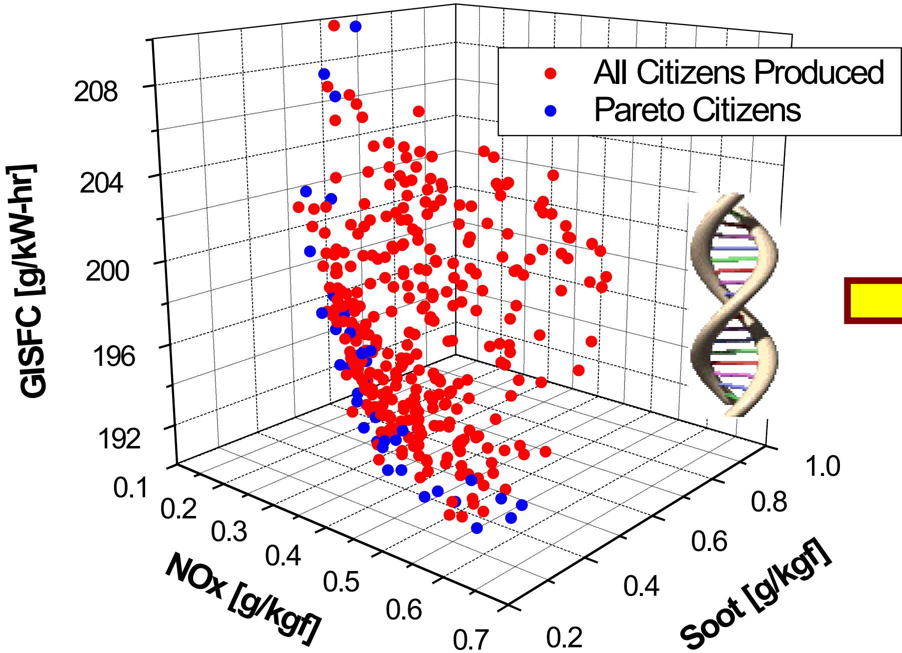
Descendants

Liu, 2006

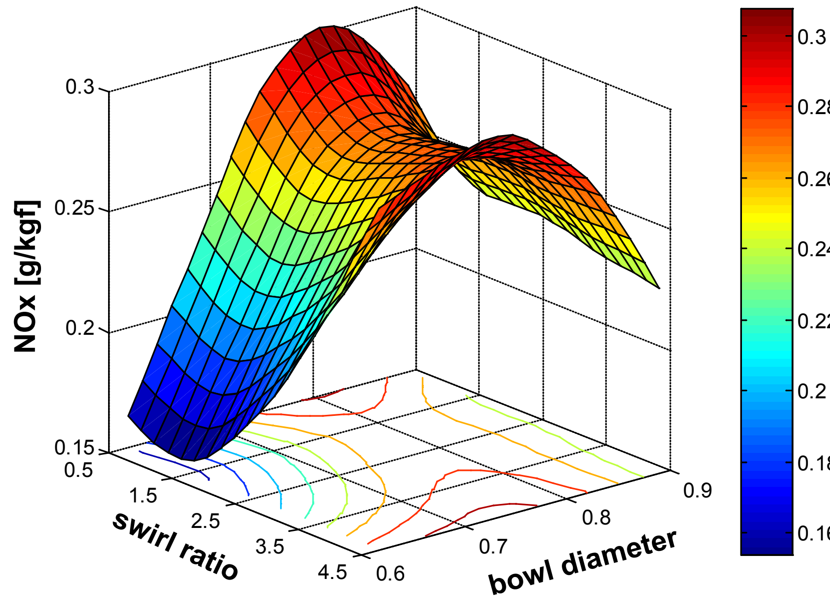
Coello, 2001

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

Regression technique suitable for handling irregular and undesigned data sets (e.g., GA data) [2]

Utilizes otherwise discarded optimization data

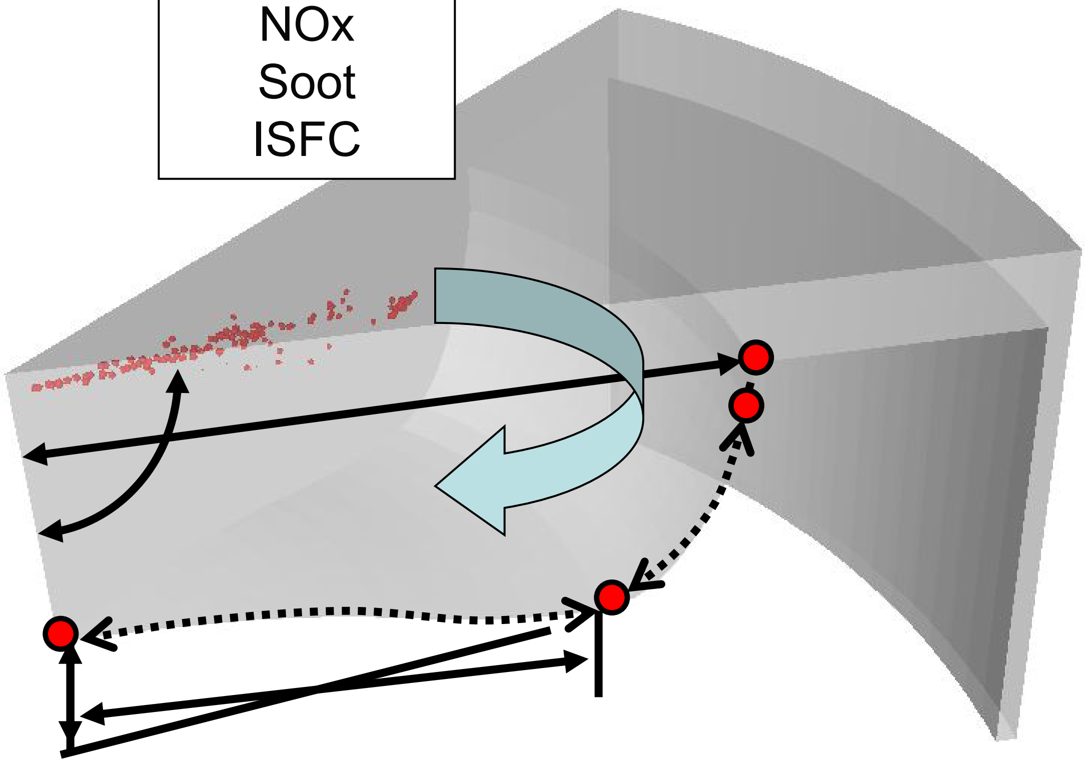
Captures magnitude of effects AND the shape of their response

Example optimization - piston bowl design

Parameters and Objectives

Genzale, 2007

Optimize:
NOx
Soot
ISFC



7 Geometry Parameters:

Pip height

Bowl diameter

ϕ of bowl bottom

4 curvature control points

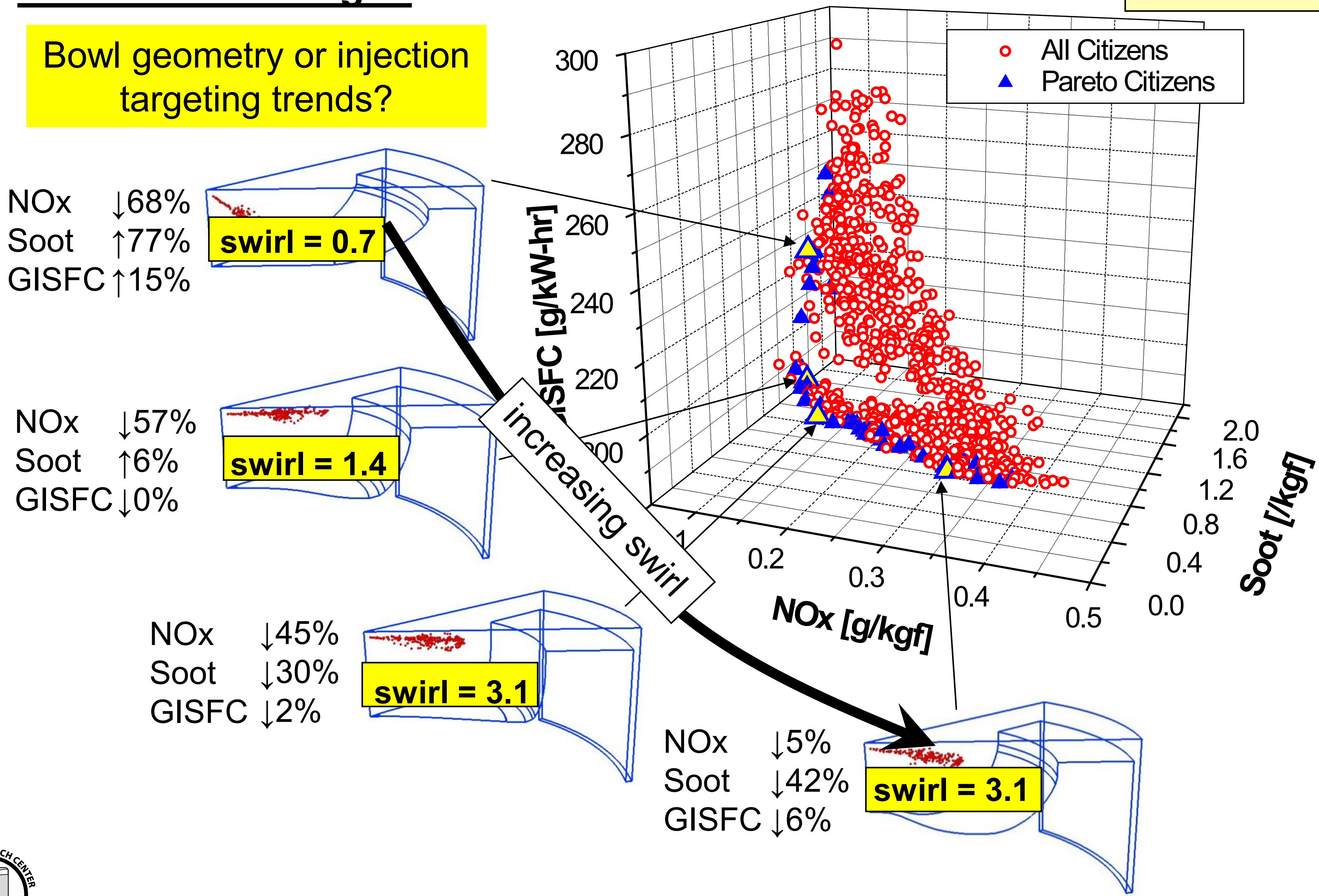
Injector Spray Angle

Swirl Ratio

Pareto front designs

Genzale, 2007

Bowl geometry or injection targeting trends?

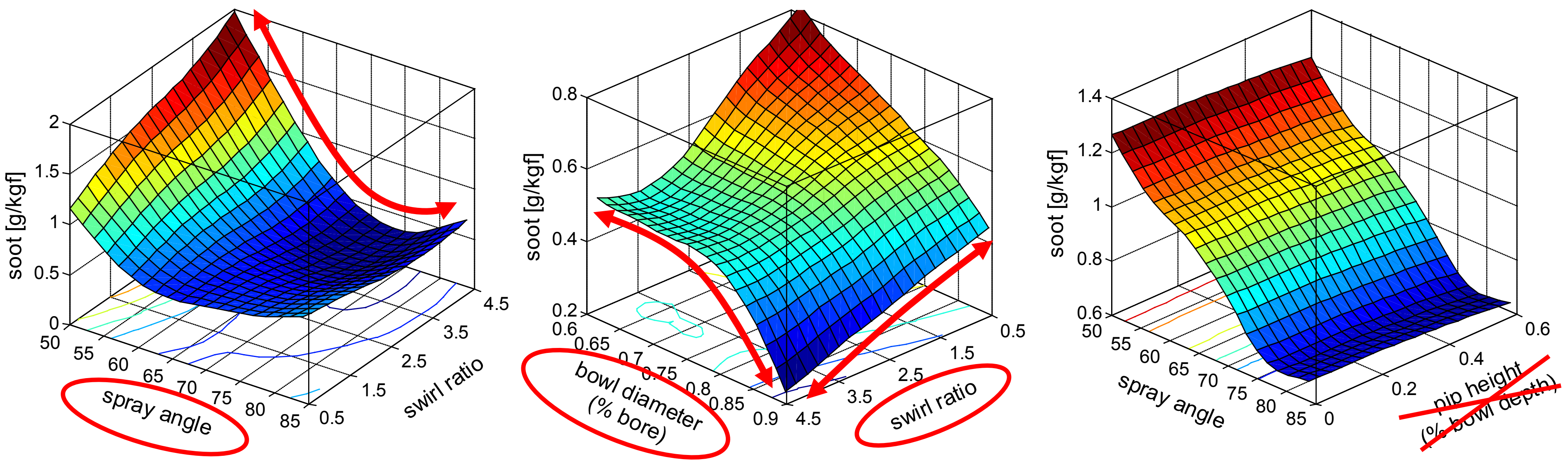


Regression – Identify dominant design parameters

Genzale, 2007

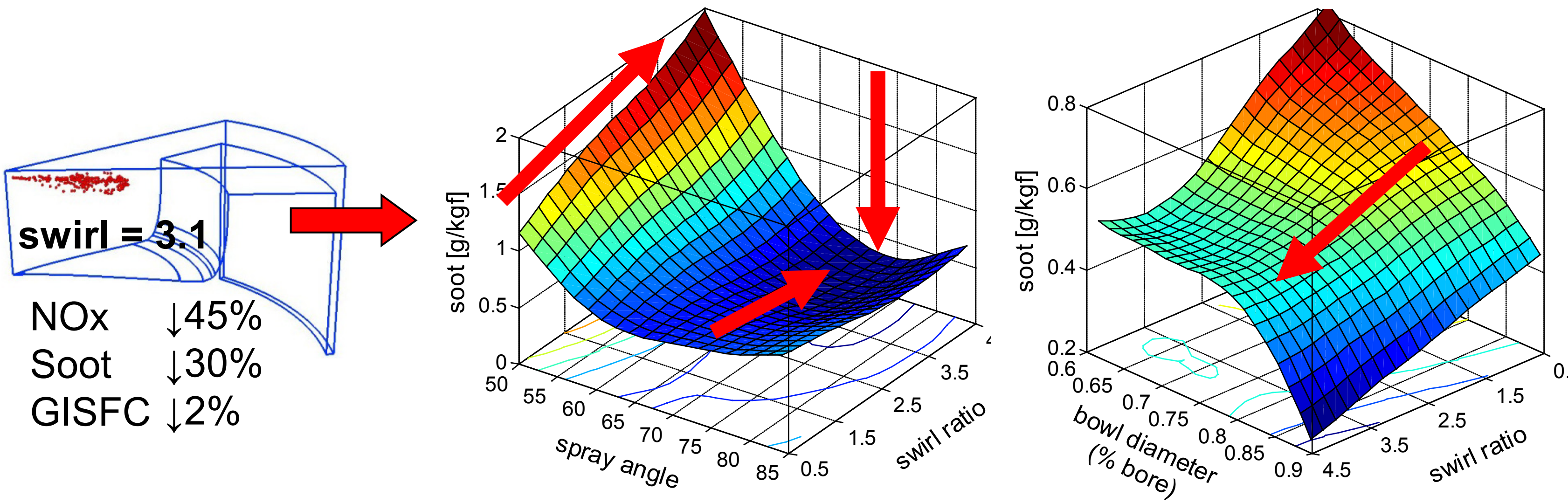
Regression fits performed for each design on the Pareto front

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



Regression – Understand Parameter Effects

Genzale, 2007



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.

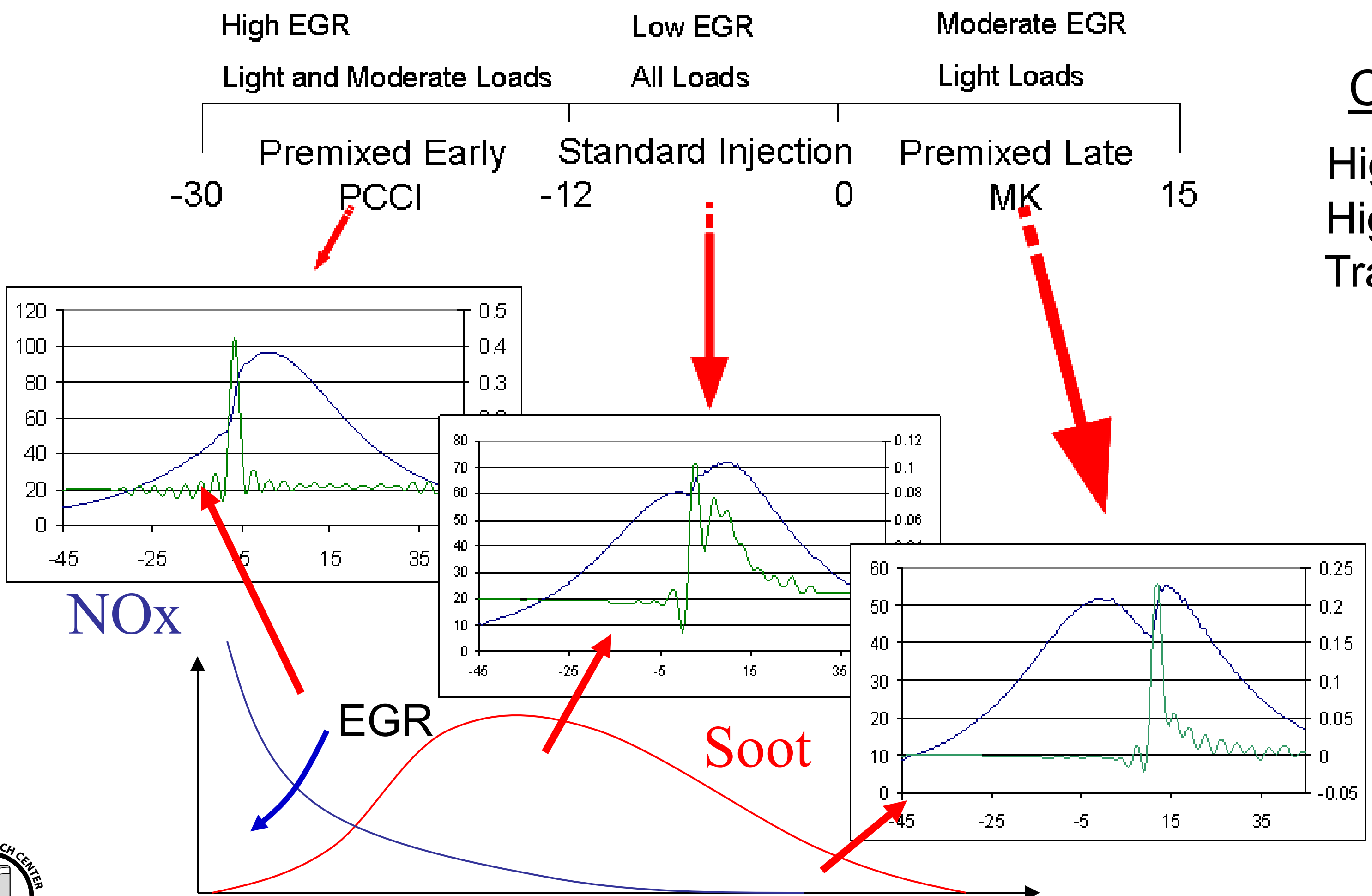
Increased swirl ratio is predicted to decrease soot at all bowl diameters.

Optimization of LTC - low temperature combustion

Klingbeil, 2003

Increased interest in advanced combustion regimes

RCCI, HCCI, PCCI, MK - offer simultaneous reduction of NOx and soot



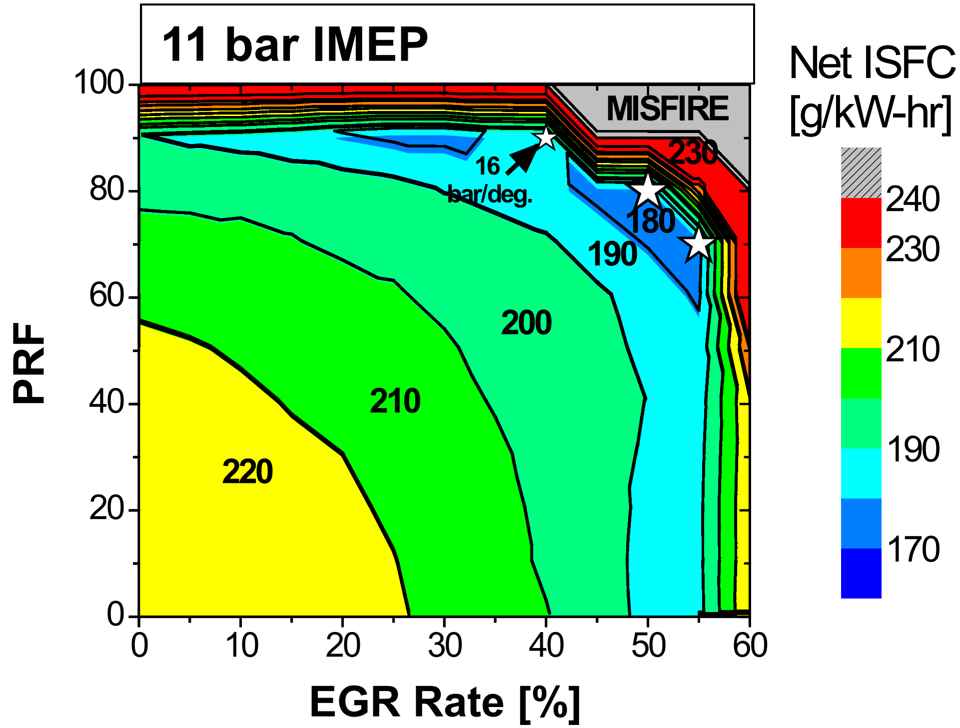
Challenges

High CO, HC
High loads
Transients

Kokjohn, 2009

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

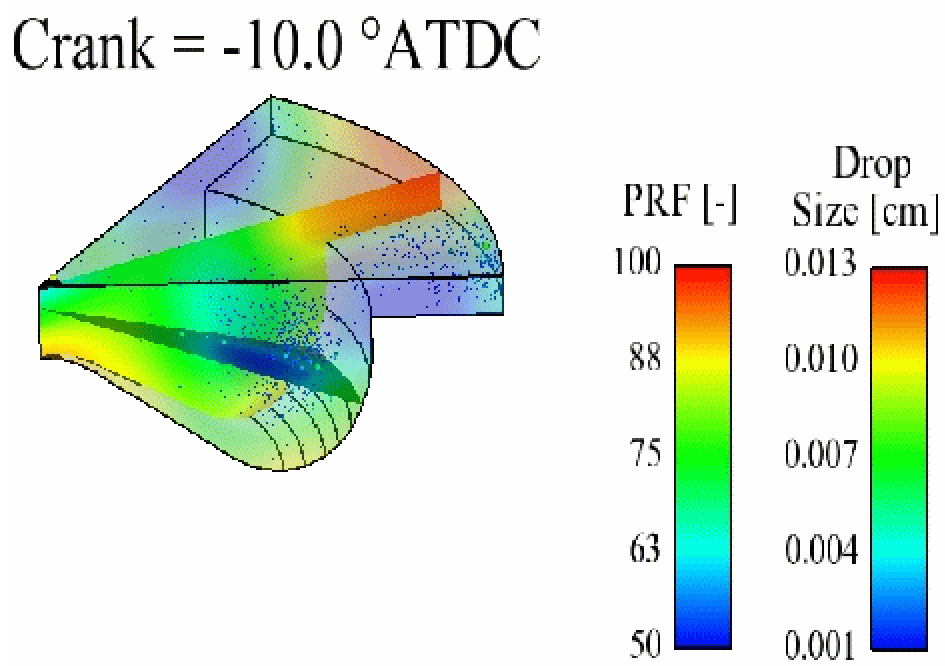


Charge preparation optimization

Premixed and Direct Injected fuel blending

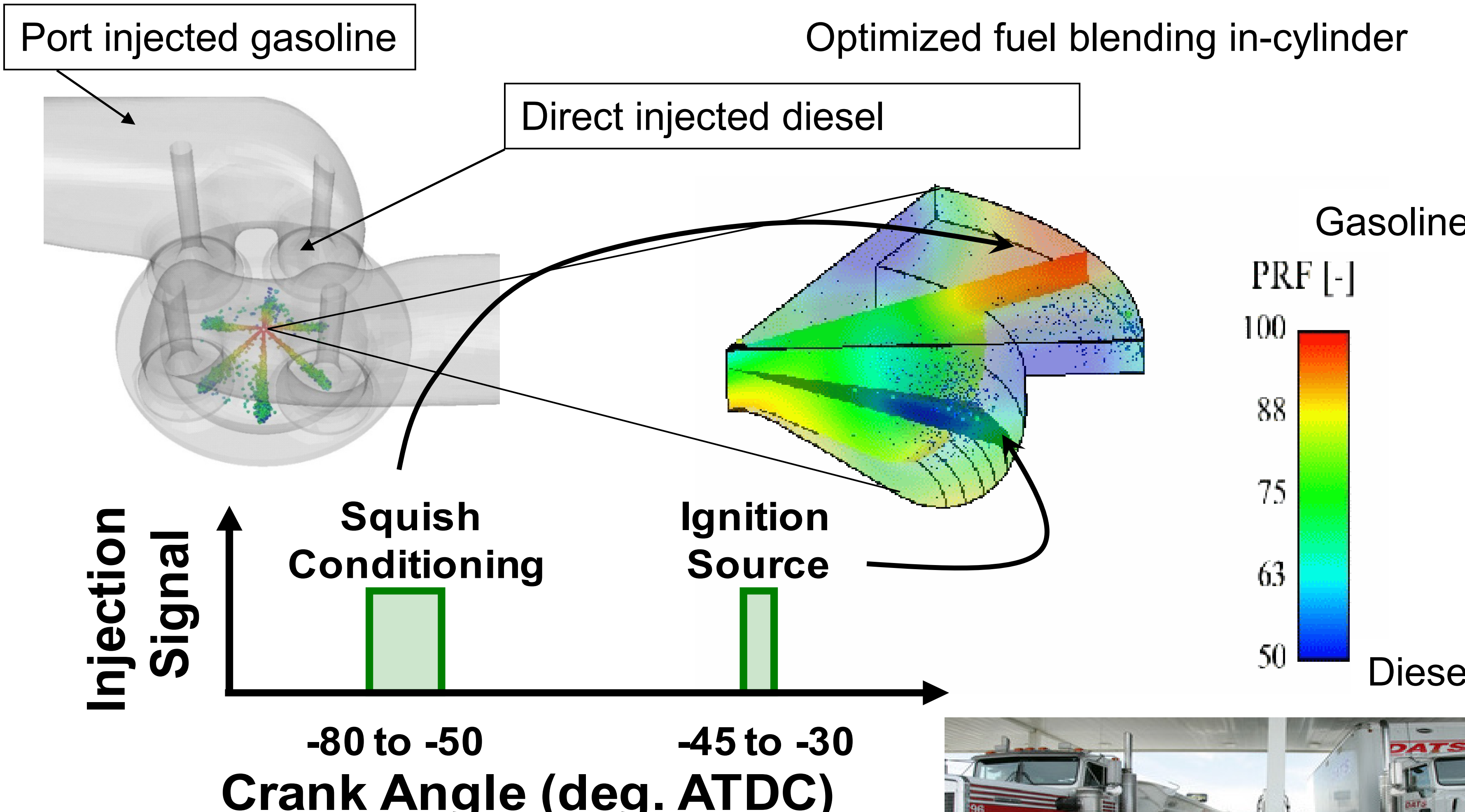
Inj. 1 Pressure	100 to 1500 bar
Inj. 2 Pressure	100 to 1500 bar
SOI 1	IVC to (SOI2-20) ºATDC
SOI 2	-50 to -30 ºATDC

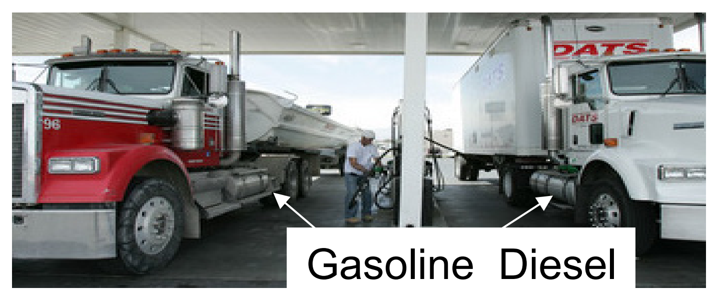
- Desirable to use traditional diesel type injector
  - Large nozzle hole (250 μm)
  - Wide angle (145° included angle)
- KIVA + Multi-Objective Genetic Algorithm (MOGA)
- Fuel reactivity and EGR from HCCI investigation (9 bar IMEP)
  - Global PRF = 65
  - EGR rate = 50%
- Five optimization parameters
- Minimize two objectives
  - Wall film amount
  - PRF Inhomogeneity
- Simulations run to 10 °BTDC
- 21 generations with a population size of 24



Kokjohn, 2009

Optimized Reactivity Controlled Compression Ignition (RCCI)

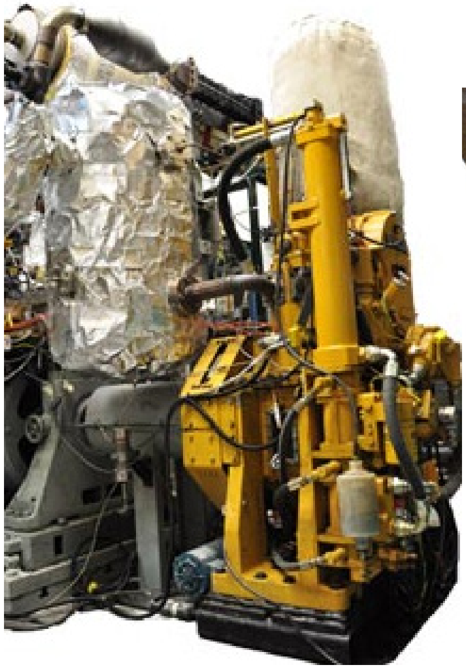


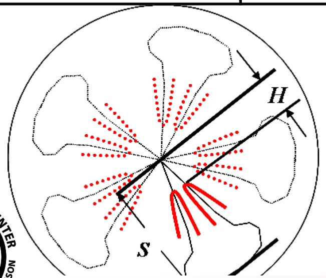


Kokjohn, 2009

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





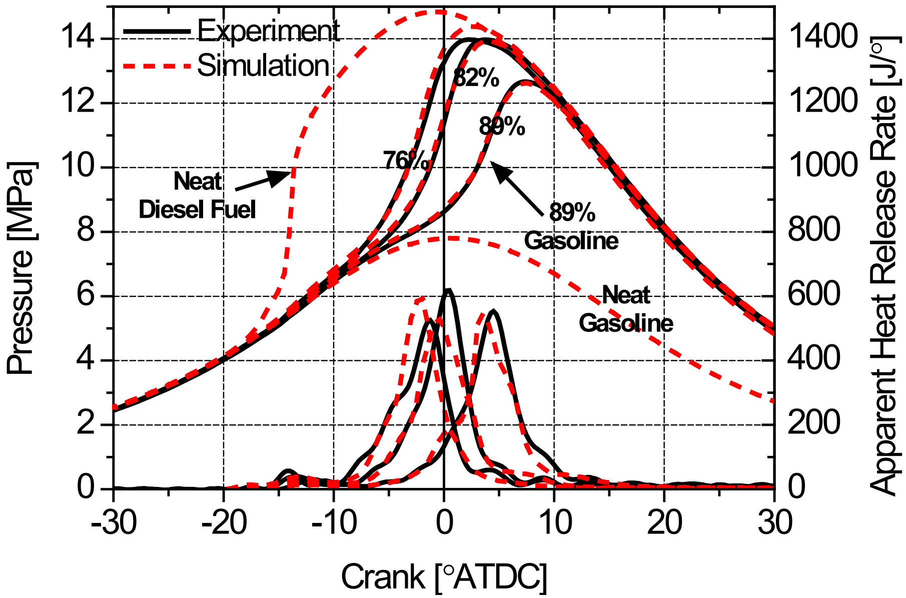
Engine size scaling
Staples, 2009

Experimental validation - HD Caterpillar SCOTE

Hanson, 2010

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



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

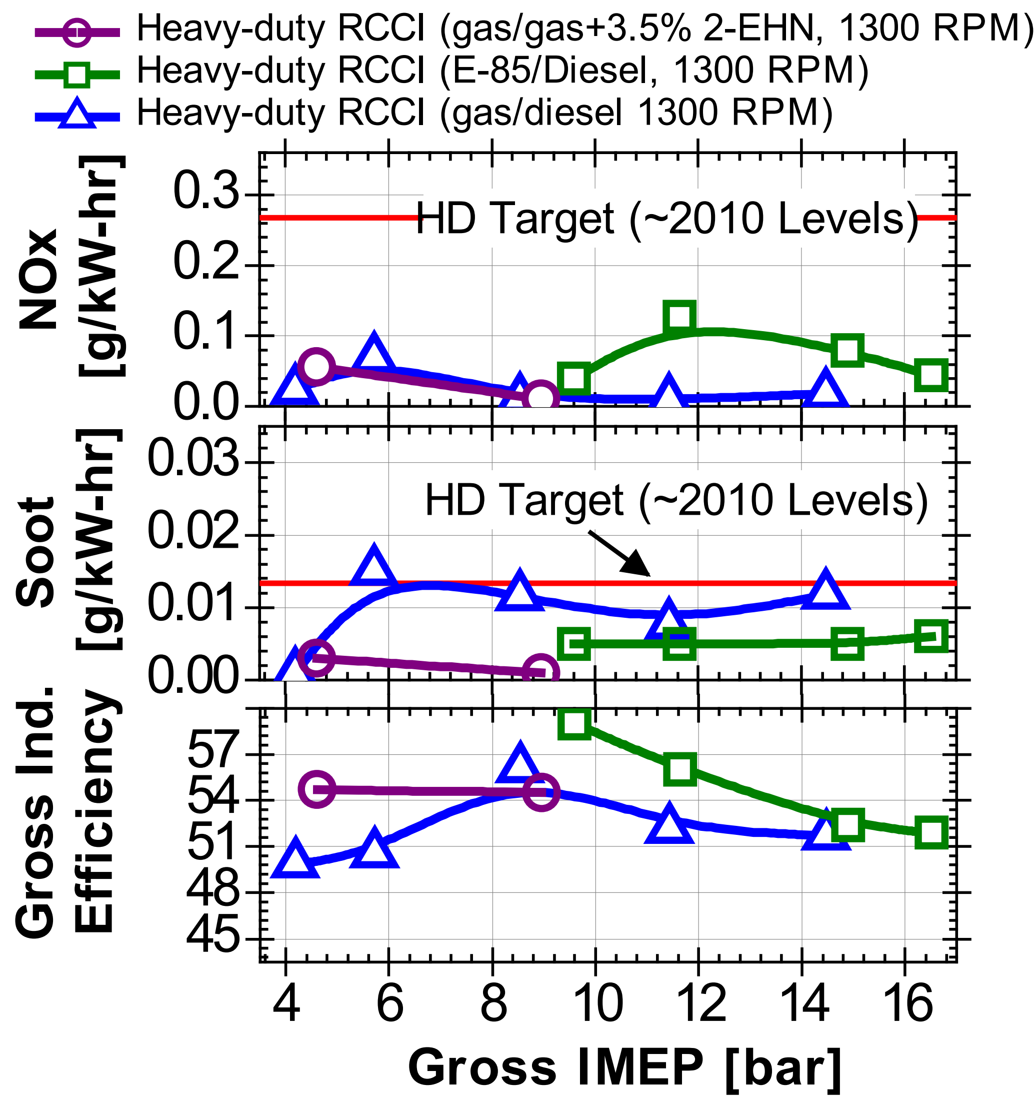
Hanson, 2011
Splitter, 2010

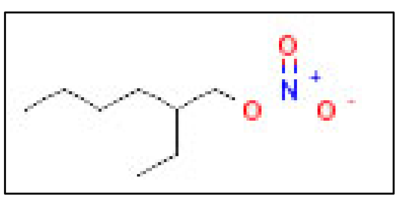
Indicated efficiency of 58±1% achieved with E85/diesel

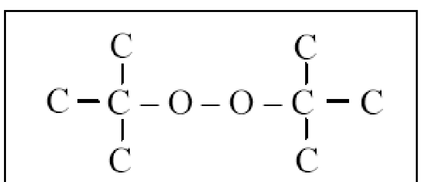
Emissions met in-cylinder, without need for after-treatment

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







Kokjohn, 2011

Dual fuel RCCI combustion – controlled HCCI

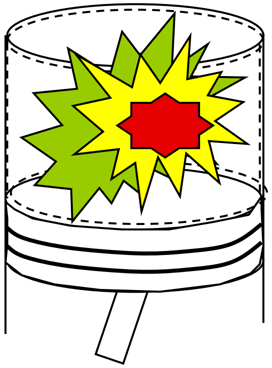
Heat release occurs in 3 stages (SAE 2010-01-0345, 2012-01-0375)

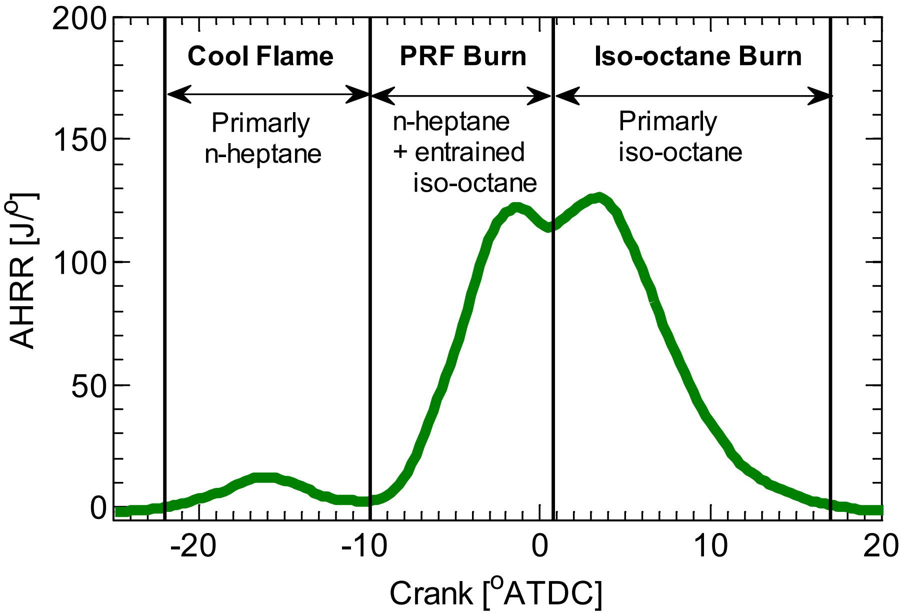
- Cool flame reactions result from diesel (n-heptane) injection
- First energy release occurs where both fuels are mixed
- Final energy release occurs where lower reactivity fuel is located

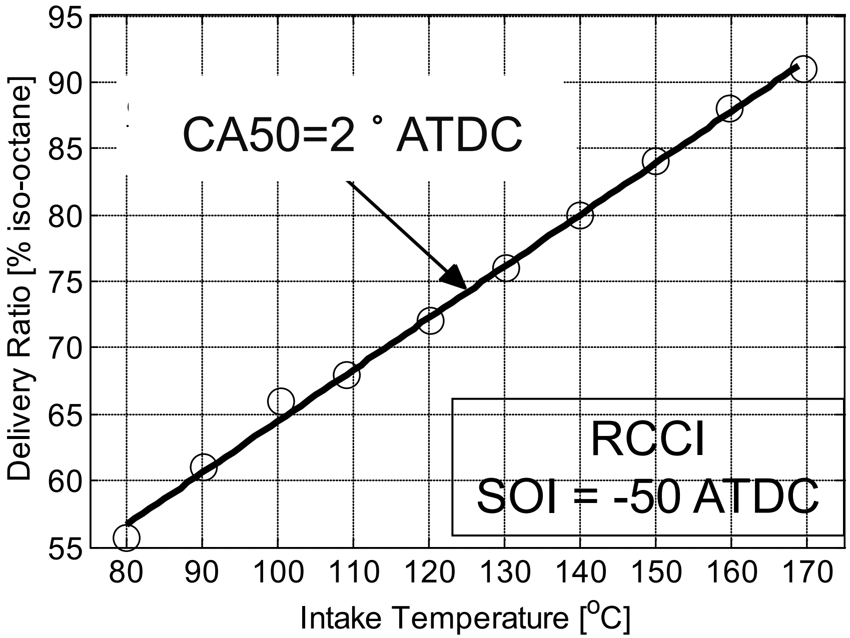
Changing fuel ratios changes relative magnitudes of stages

Fueling ratio provides "next cycle" CA50 transient control

RCCI

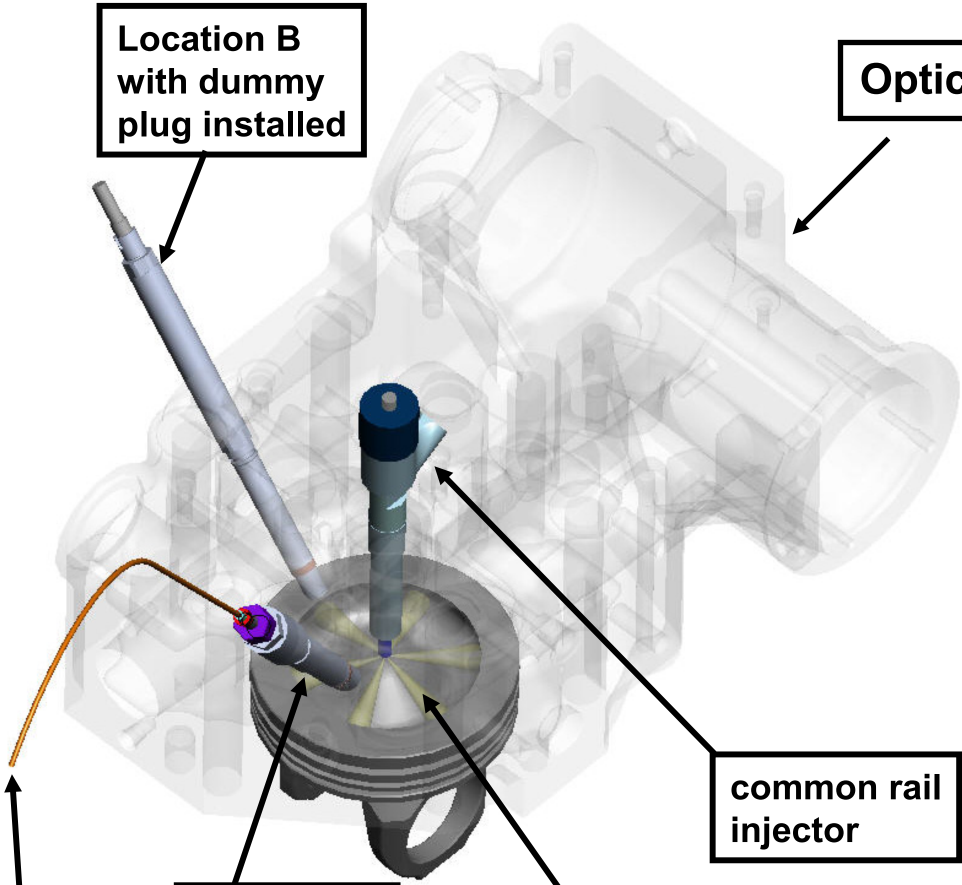






Splitter, 2010

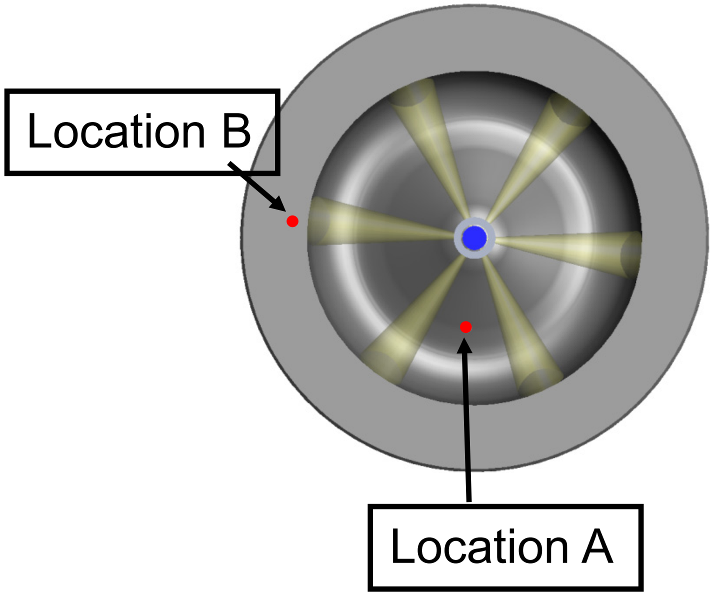
Understanding RCCI combustion

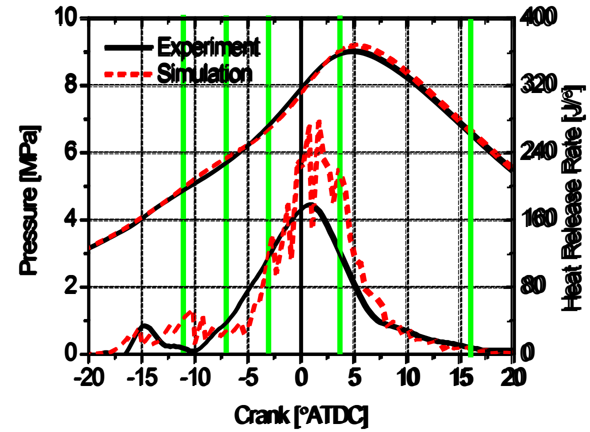


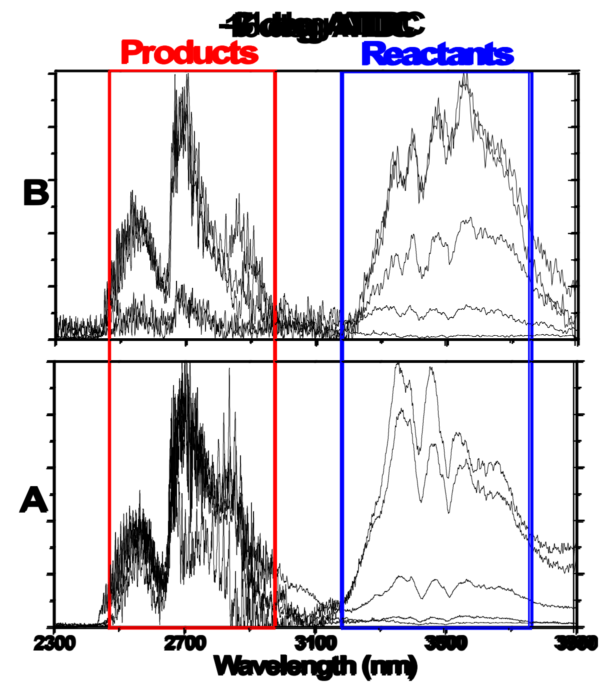
Optical Cylinder Head

Splitter, 2010

Understanding RCCI combustion







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

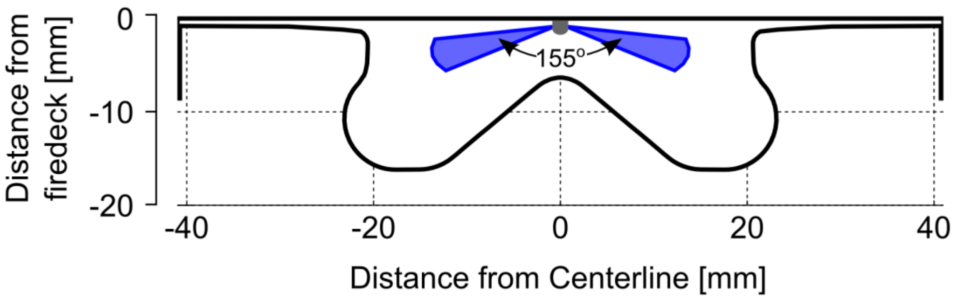
Fuel decomposition and combustion products form at a slower rate at location B, extending combustion duration

Kokjohn, 2013

Light-duty drive-cycle performance

- Compare conventional diesel combustion (CDC) and Reactivity Controlled Compression Ignition (RCCI) combustion
- Compare at same operating conditions (CR, boost, IMT, swirl..)
- ERC KIVA-Chemkin Code
  - Reduced primary reference fuel used to model diesel and gasoline kinetics
  - Suite of improved ERC spray models

Combustion Chamber Geometry



Diesel fuel injector specifications

Type	Bosch common rail
Actuation type	Solenoid
Included angle	155°
Number of holes	7
Hole size (μm)	141

Engine specifications

Base engine type	GM 1.9 L
Bore (mm)	82
Stroke (mm)	90.4
Connecting rod length (mm)	145.5
Squish height (mm)	0.617
Displacement (L)	0.4774
Compression ratio	16.7:1
Swirl ratio	1.5 to 3.2
IVC (°ATDC)	-132°
EVO (°ATDC)	112°

Comparison - RCCI vs. conventional diesel

Kokjohn, 2013

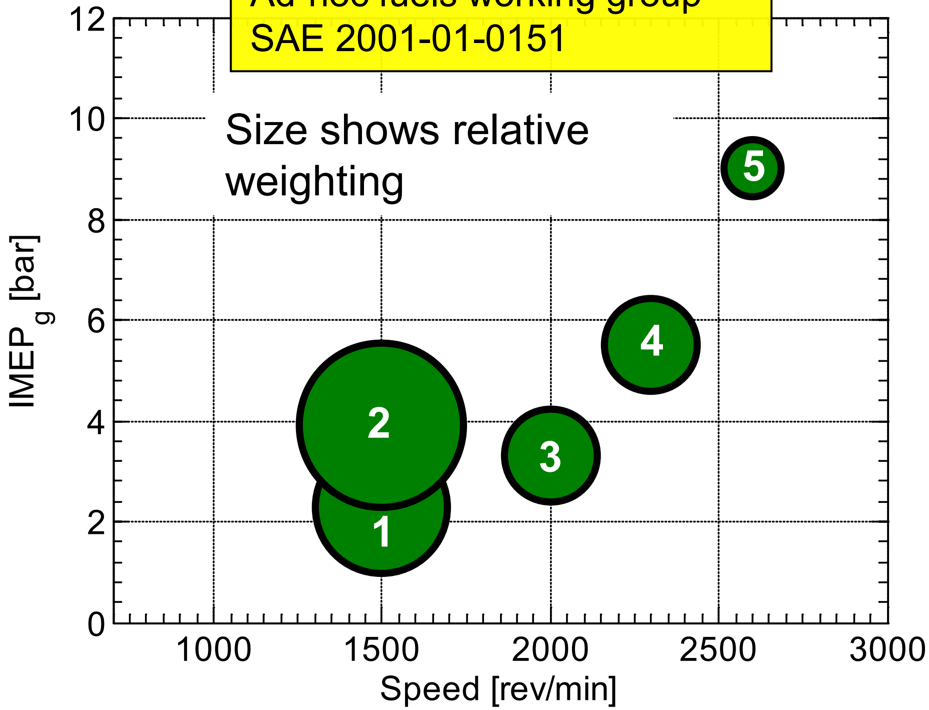
Five operating points of Ad-hoc fuels working group

Tier 2 bin 5 NOx targets from

Cooper, SAE 2006-01-1145

(assumes 3500lb Passenger Car)

Evaluate NOx / fuel efficiency tradeoff using SCR for CDC



Mode	Speed (rpm)	IMEP (bar)	CDC Baseline NOx (g/kgf) *	NOx Target (g/kgf)
1	1500	2	1.3	0.2
2	1500	3.9	0.9	0.4
3	2000	3.3	1.1	0.3
4	2300	5.5	8.4	0.6
5	2600	9	17.2	1.2

Assumptions

Diesel exhaust fluid (DEF) consumption is 1% per g/kW-hr NOx reduction

Johnson, SAE 2011-01-0304

No penalty for DPF regeneration

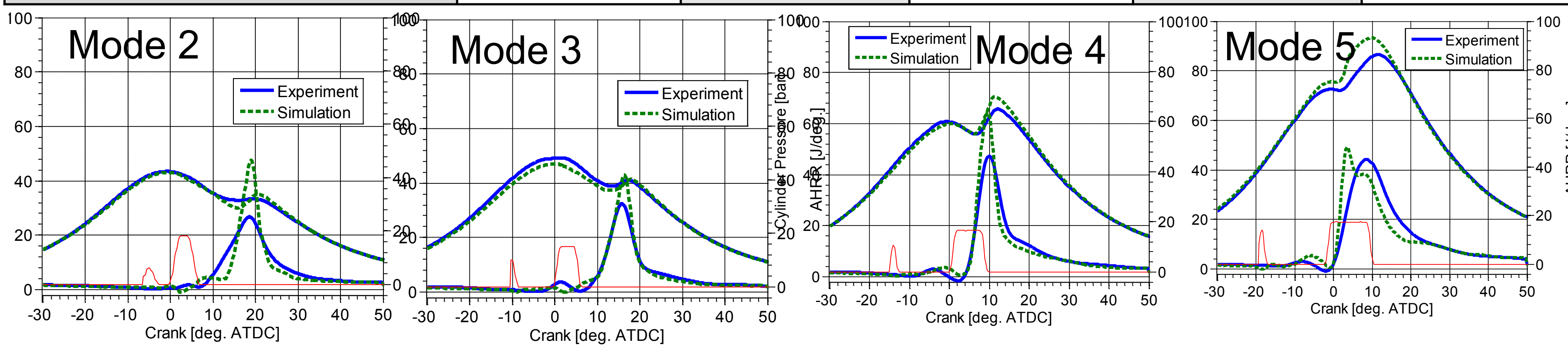
UHC and CO only contribute to reduced work

* Baseline CDC Euro 4: Hanson, SAE 2012-01-0380

Euro 4 operating conditions - conventional diesel

Kokjohn, 2013

Model validation	CDC Operating Conditions *				
Mode	1	2	3	4	5
IMEPg (bar)	2.3	3.9	3.3	5.5	9
Speed (rev/min)	1500	1500	2000	2300	2600
Total Fuel (mg/inj.)	5.6	9.5	8	13.3	20.9
Intake Temp. (deg. C)	60	60	70	67	64
Intake Press. (bar abs.)	1	1	1	1.3	1.6
EGR Rate (%)	47	38	42	25	15
CR Inj. Pressure (bar)	330	400	500	780	1100
Pilot SOI advance (°CA)	7	7	11	15	18
Main SOI (° ATDC) (actual)	-0.9	0	0.1	0.5	-1.8
Percent of DI fuel in Pilot (%)	20	15	15	10	10

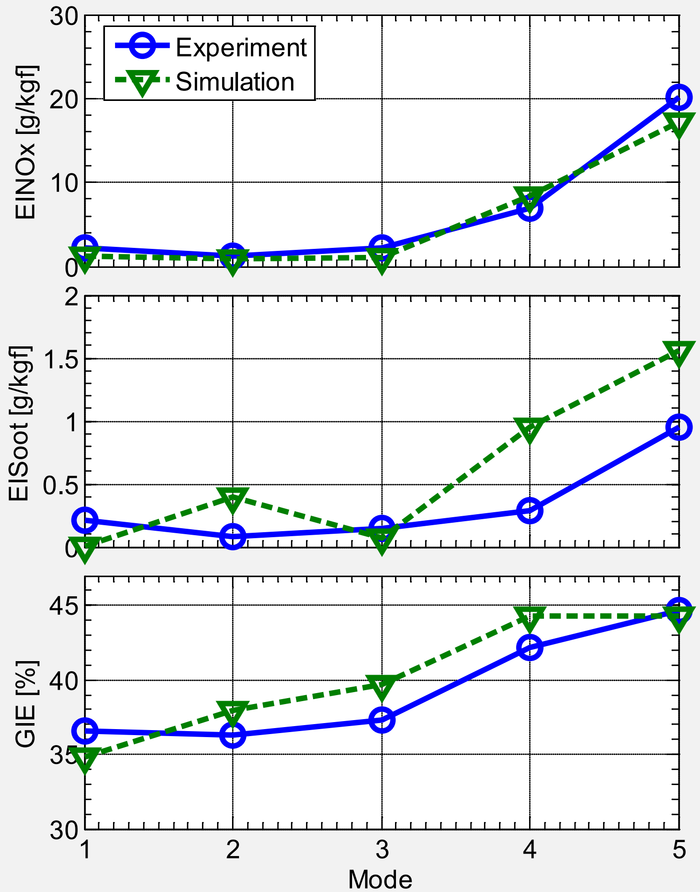


* Baseline CDC Euro 4: Hanson, SAE 2012-01-0380

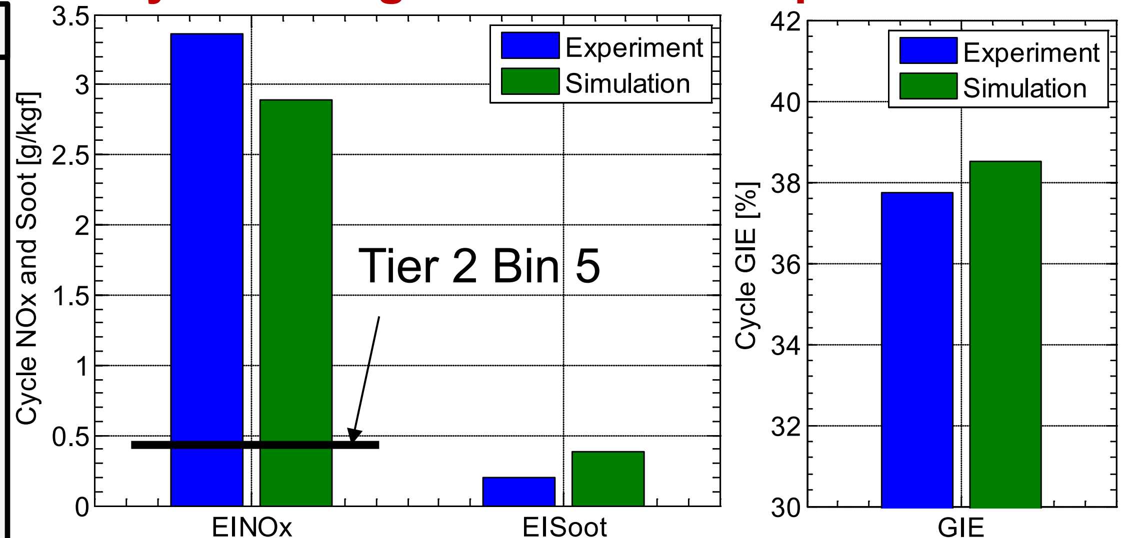
Kokjohn, 2013

Model validation (Euro 4)

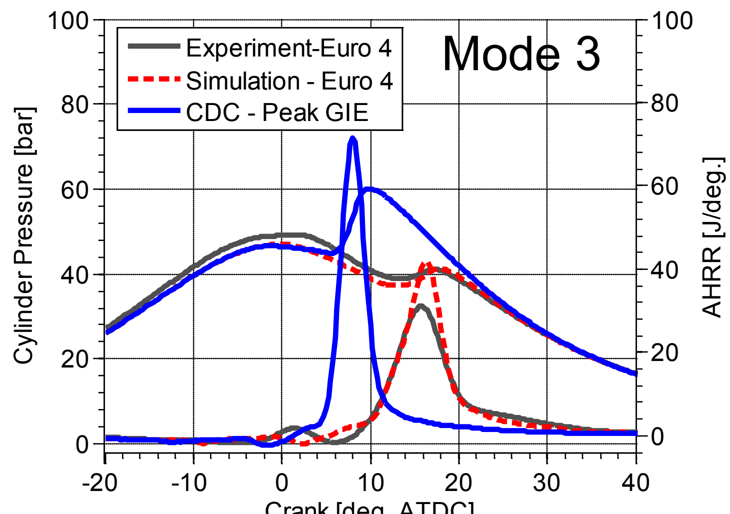
Comparison at 5 Modes



Cycle average emissions and performance



Optimized CDC with SCR for Tier 2 Bin 5



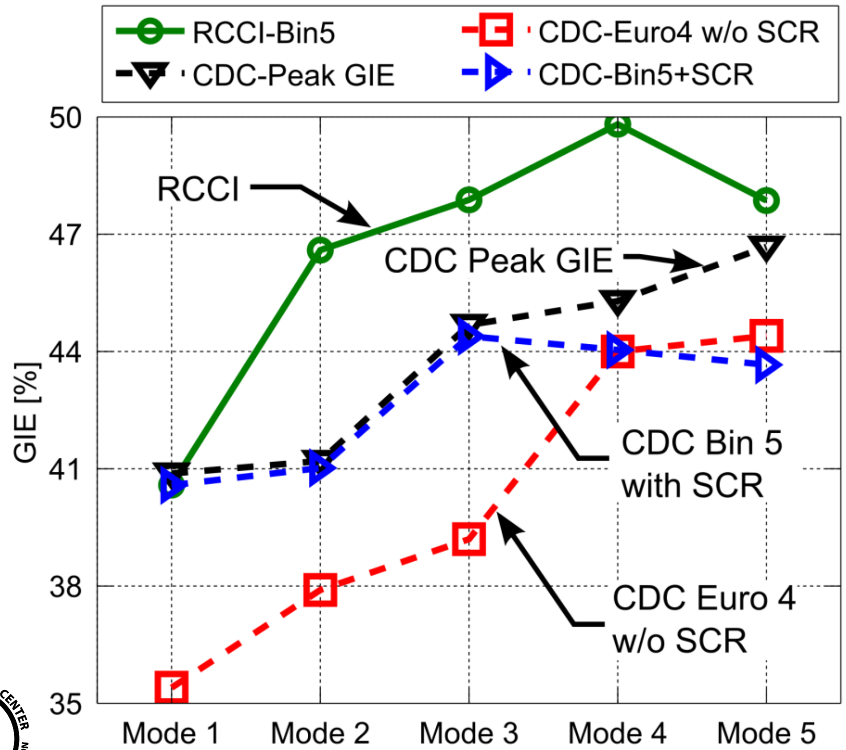
CDC optimized GIE has higher allowable PPRR (advanced SOI) than Euro 4 calibration

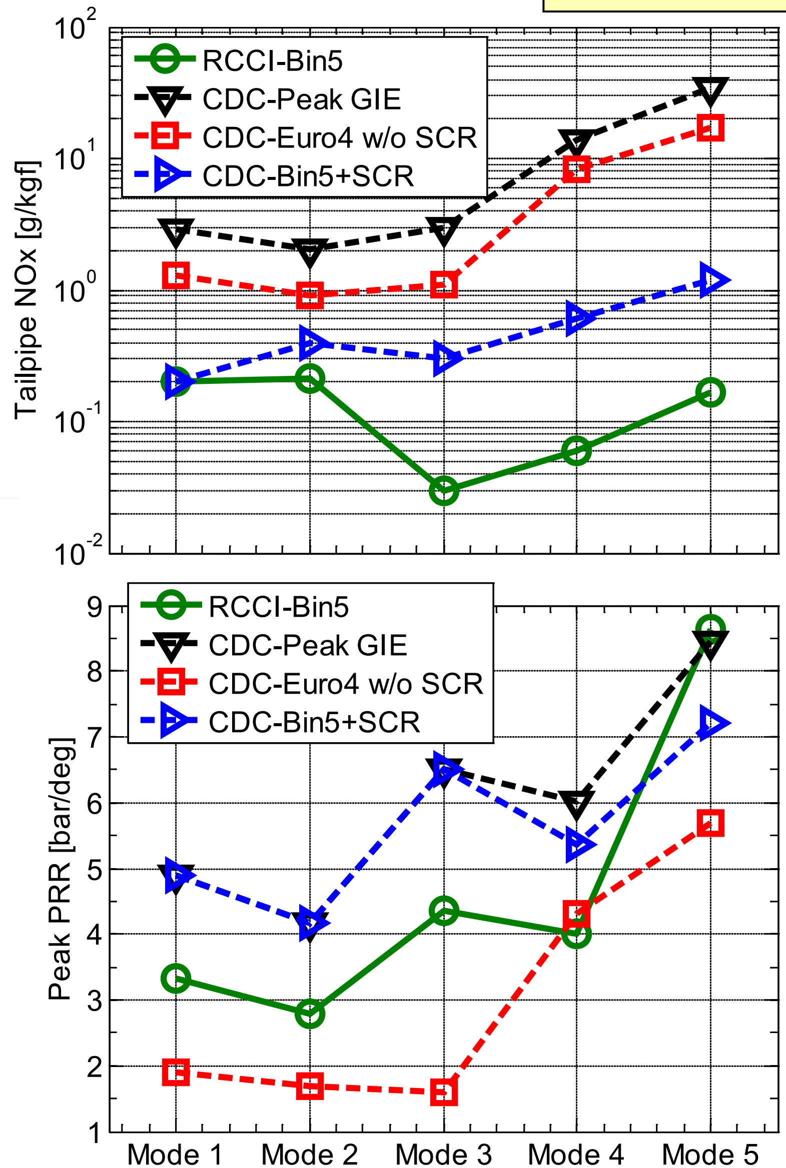
Weighted average: $$E_{cycle} = \frac{\sum_{\text{imode}=1}^{5} E_{\text{imode}} Weight_{\text{imode}}}{\sum_{\text{imode}=1}^{5} Weight_{\text{imode}}}$$

Comparison of efficiency, NOx and PRR

Kokjohn, 2013

- Target NOx at Tier 2 Bin 5
- RCCI meets NOx targets without DEF
- DEF NOx after-treatment has small efficiency penalty at light-load (2 to 4 bar IMEP) and moderate EGR (~40%)
- DEF penalty is larger above 5 bar IMEP where EGR is below 40%



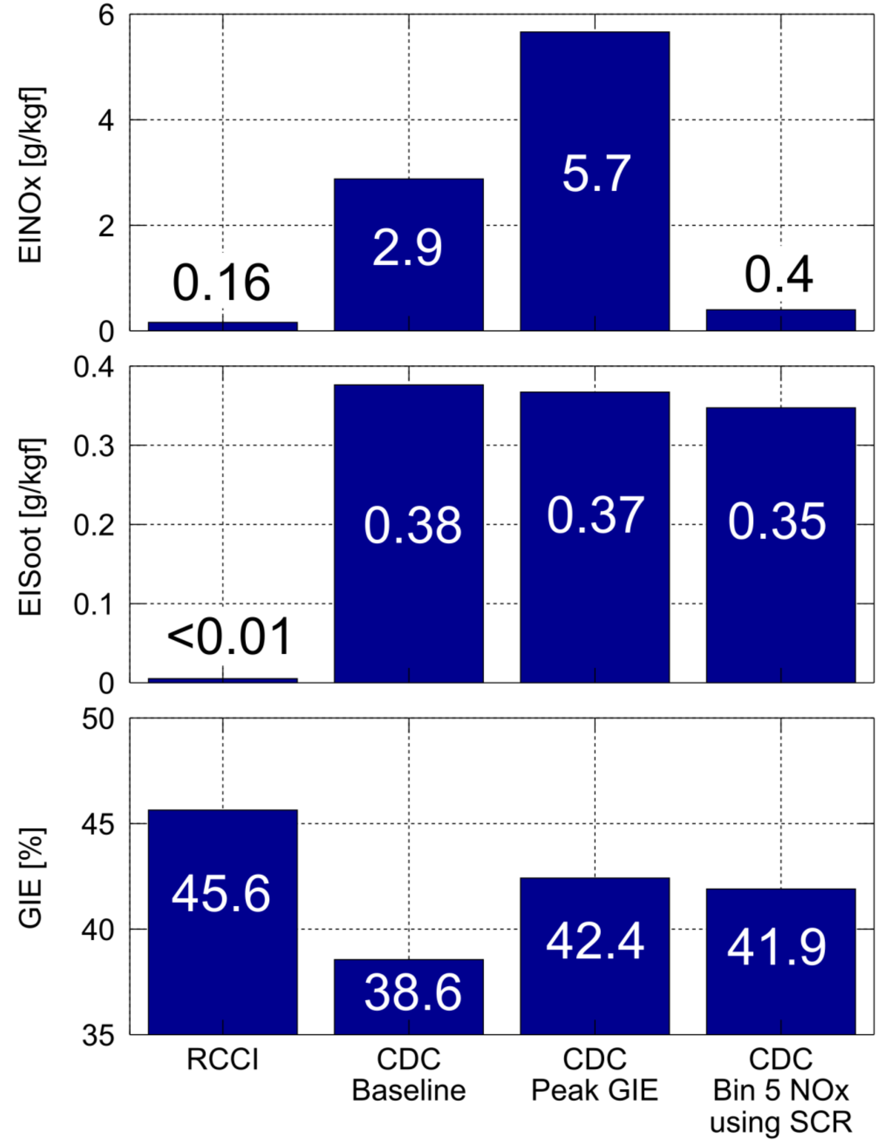


Cycle averaged NOx, Soot and GIE

Kokjohn, 2013

- RCCI and CDC compared at baseline and Tier 2 Bin 5 NOx
  - CDC NOx-GIE tradeoff controlled by main injection timing
- RCCI meets NOx targets without after-treatment
- RCCI gives ~8% improvement in fuel consumption over CDC+SCR
- RCCI soot is an order of magnitude lower than CDC+SCR
- RCCI HC is ~5 times higher than CDC+SCR
  - Currently addressing methods to reduce HC emissions
  - Crevice-originated HC emissions

    Splitter, SAE 2012-01-0383
  - Thermal barrier coated piston



Splitter, 2013

Limits of dual-fuel RCCI efficiency ?

- Calibrate 0-D code with CR=14.88 experiments
- Use code to determine conditions needed to reach ~ 60% GTE

Results:

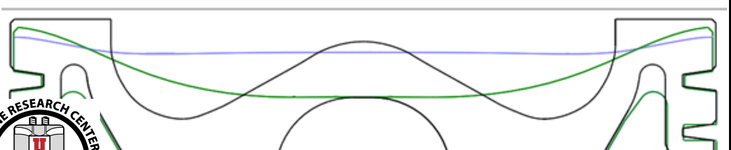
~60% GTE possible with:

High Cr

Lean operation (Φ<0.3)

50% reduction in heat transfer & combustion losses

- Deactivate under-piston oil jet cooling



	Exp.	GT POWER
Compression ratio	**14.88**	**14.88**
IMEPn (bar)	**8.00**	**7.86**
Fueling (mg/cyc)	**87.13**	**87.13**
Gross Therm Eff. (%)	**54.3**	**54.5**
Net Therm Eff. (%)	**52.0**	**52.1**
BTE (%)	**45.3**	**45.1**
FMEP (bar)	**1.03**	**1.0**
Convection HX	**N/A**	**0.4**
Comb. Eff. (%)	**98**	**98**
Intake Pressure (bar)	**1.5**	**1.5**
Exhaust Pressure (bar)	**1.625**	**1.625**
Turbo eff. (air filter + DOC)	**67.5**	**62.3**

Splitter, 2013

Ultra-high efficiency dual-fuel RCCI combustion

	GTE (%)	IMEPg (bar)	NTE (%)	IMEPn (bar)
EXP (pt. 83)	59.1	6.82	55.0	6.27
GT Power HX =0.2	58.8	6.79	54.8	6.25
GT Power HX =0.4	56.7	6.55	52.8	6.02

High efficiency demonstrated!

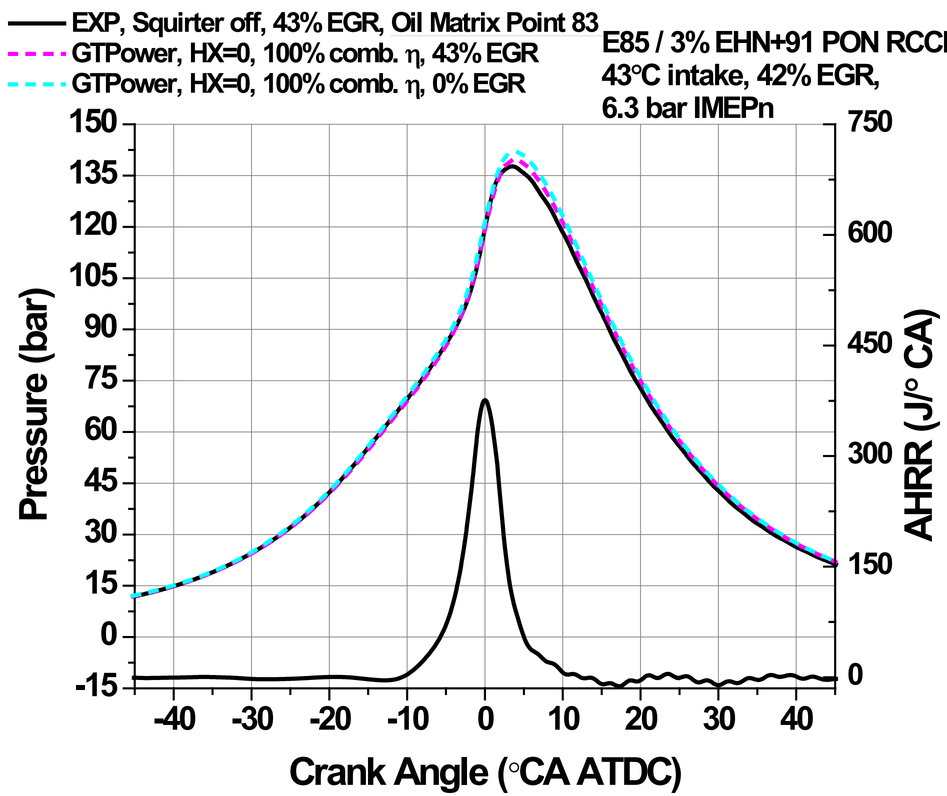
Simulation heat transfer tuned to match data

14.88:1 required HX = 0.4

18.7:1 required HX = 0.3

(Pancake ~1.2 less surface area)

18.7:1 w/o oil cooling HX = 0.2



	GTE (%)	IMEPg (bar)	NTE (%)	IMEPn (bar)
Experiment	59.1	6.82	55.0	6.27
Model, HX =0 100% comb. η	62.4	7.12	58.5	6.85
Model, HX =0 100% comb.η, 0% EGR	63.4	7.23	61.0	6.95

94% of maximum theoretical cycle efficiency achieved !

Splitter, "RCCI Engine Operation Towards 60% Thermal Efficiency", SAE 2013-01-0279

UW-Madison RCCI series hybrid vehicle

2009 Saturn Vue, V6 FWD base model → GM 1.9L diesel engine

Spannbauer, 2014
Reitz, 2014,
Hanson, 2015, 2017

SAE 2015-01-0837
Based on hot-start HWFET results, the vehicle is estimated to reach US EPA Tier2 bin5 NOx emissions with 53.5 mpg (4.4L/100km)

Installation of 7.5 gal. gasoline and diesel tanks

Closure

Availability of cheap energy has led to distorted world economies/priorities

7.2 Billion people: 1909 Haber-Bosch process making NH_3 for fertilizer

Next 30-40 years will require major innovations in IC engines

- dwindling resources and minimized environmental impact
- current energy usage rates are clearly unsustainable.

Many energy "solutions" (battery, fuel cell, nuclear) are only short term and resources are better saved for future generations

But, significant improvements in IC engines are still possible through research!

However, the only really long-term sustainable energy source is solar hydrogen.
But, a switch to a H_2 economy will take considerable time and effort.
Until this occurs, research on more efficient usage of fossil and other fuels is urgently needed!

"I'd put my money on the sun and solar energy. What a source of power!
I hope we don't have to wait until oil and coal run out before we tackle that."
Thomas Edison (1931) in conversation with Henry Ford and Harvey Firestone.

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