High Efficiency Fuel Reactivity Controlled Compression Ignition (RCCI) Combustion

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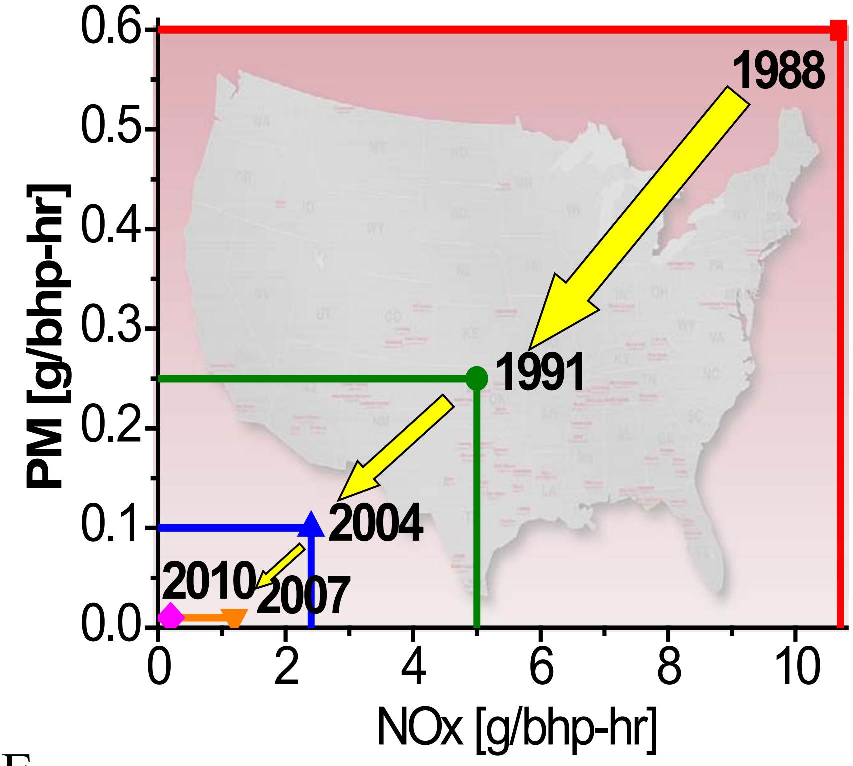
DOE Sandia Labs & University Project EE0000202
Sage Kokjohn, Derek Splitter, Reed Hanson

IC Engine thermal efficiency = work output/energy input

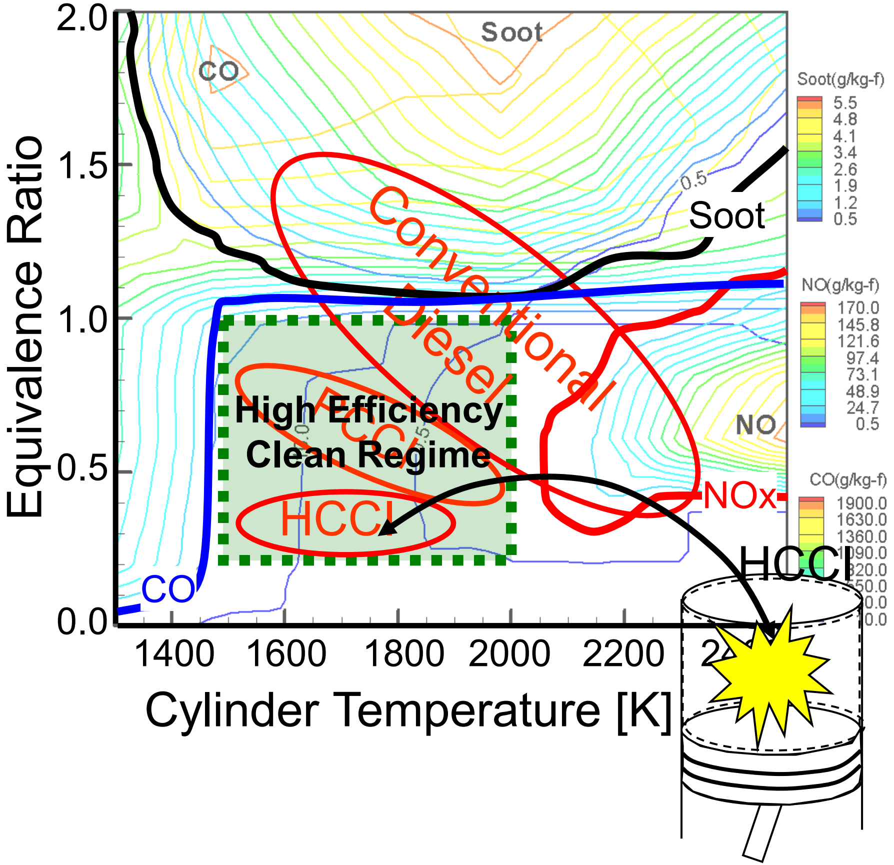
- SI gasoline engine with 3-Way Catalyst:
  Thermal Efficiency ~30%
- Diesel engines are the most efficient engines in existence:
  Thermal Efficiency ~ 40-50%



- Widely used commercially
- Can efficiencies be increased?
  DOE "SuperTruck" Goal HD 55% BTE
- Stringent emission standards

New combustion regimes

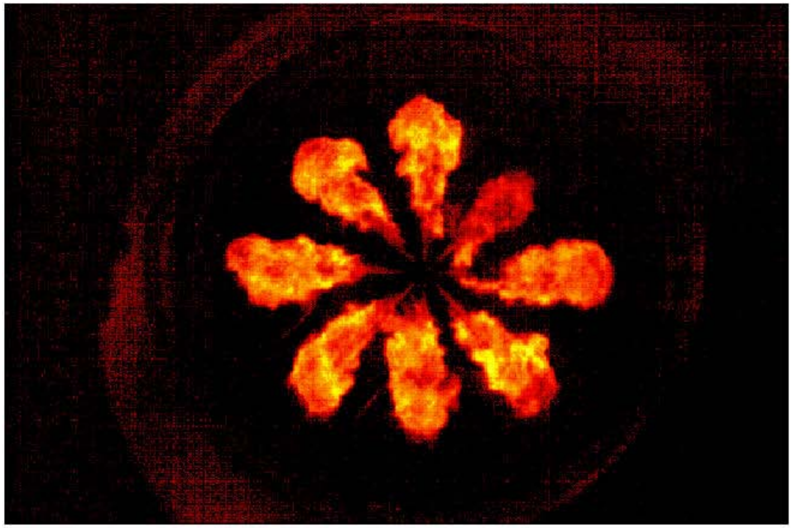
KIVA Simulations – Park & Reitz CST 2007



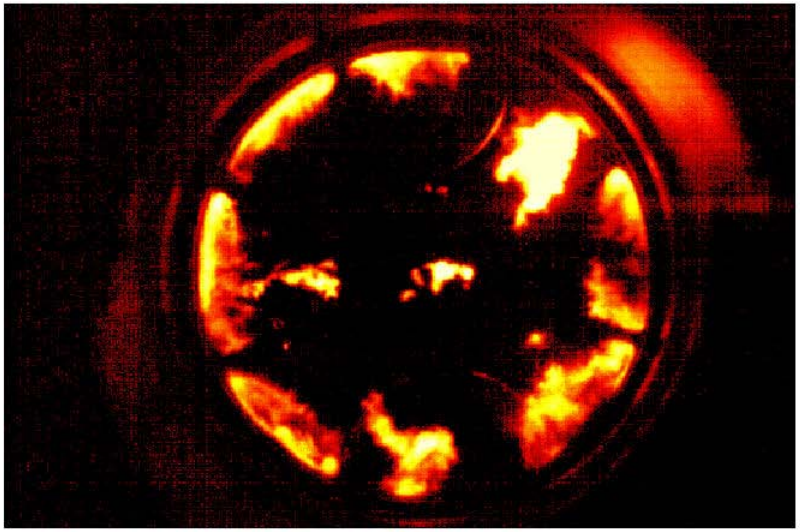
Requires precise charge preparation and combustion control mechanisms
(for auto-ignition and combustion timing)

*Singh, Musculus, Reitz: Combust&Flame, 2009

Conventional diesel *



Early injection PCCI



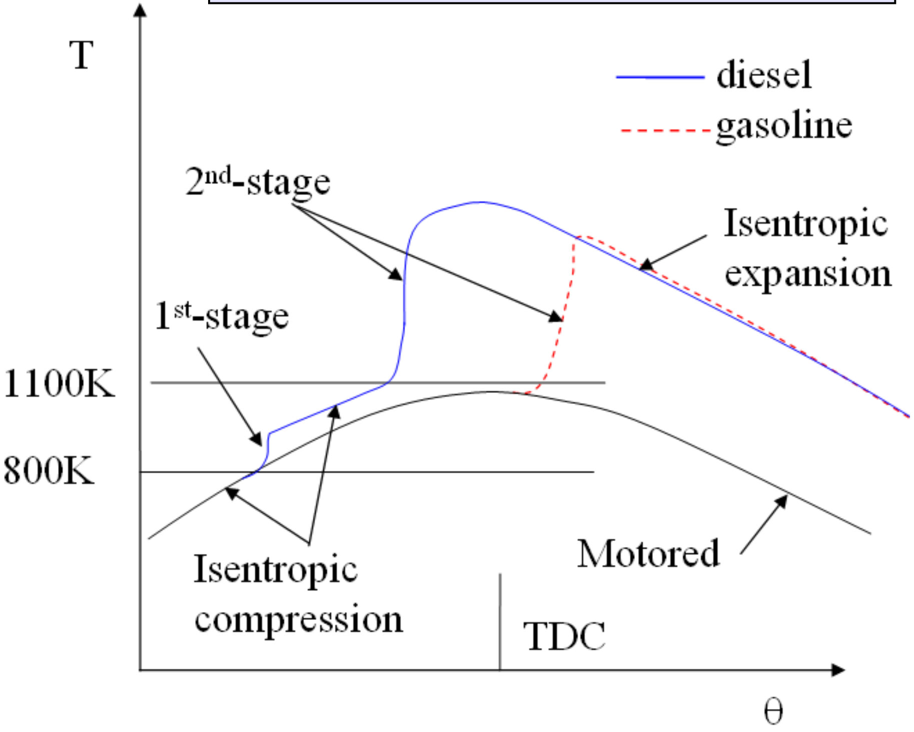
What is the best fuel for kinetics controlled PCCI?

- Diesel fuel ignites easily – difficult to vaporize
  - ❑ Good for low load premixed operation
  - ❑ Causes combustion to occur too early at high load → load limit
- Gasoline is difficult to ignite – vaporizes easily
  - ❑ Allows extension to higher load
  - ❑ Poor combustion at low load
- Both have benefits and drawbacks

→ Dual-fuel CI combustion

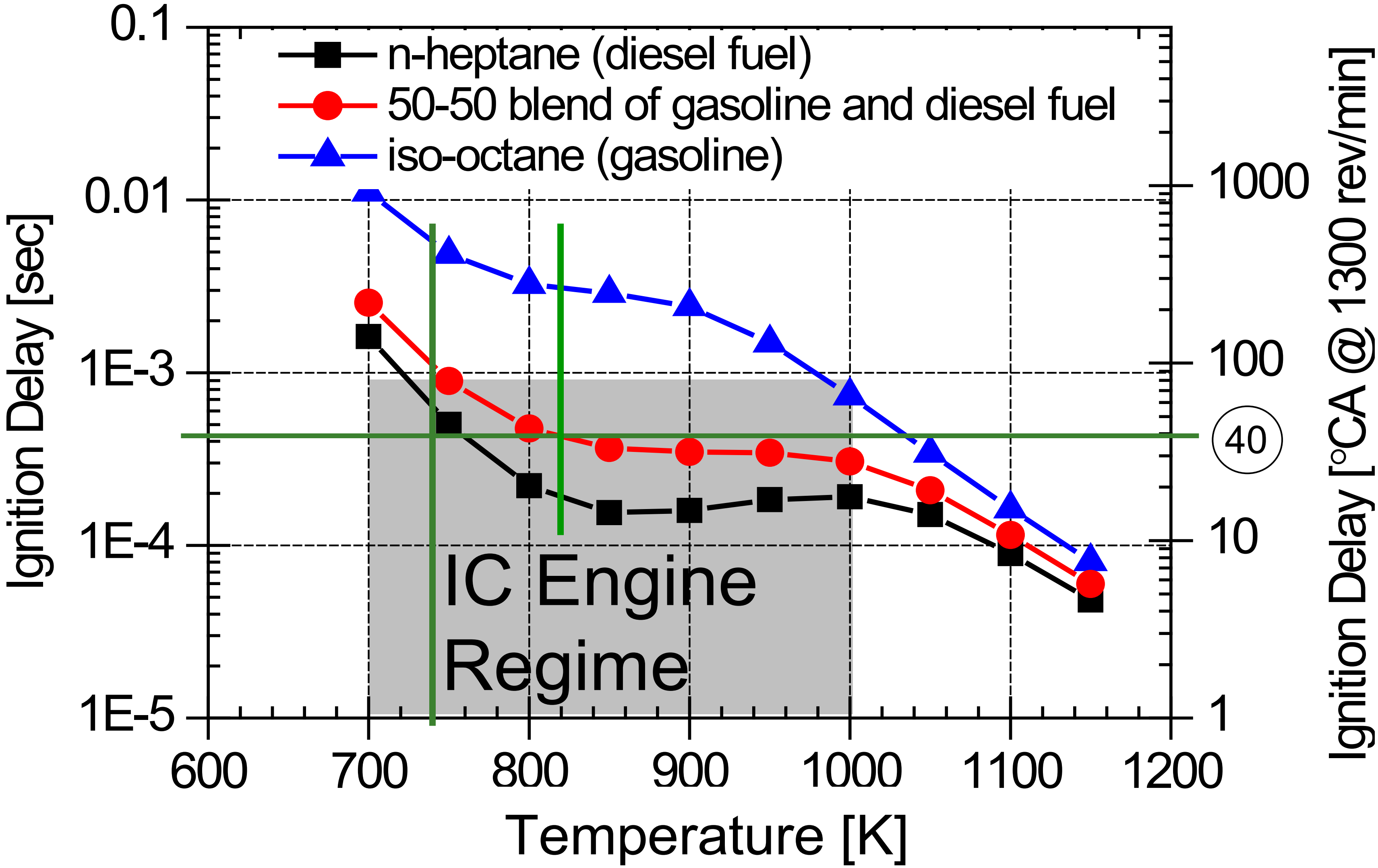
- Emissions regs. met in-cylinder
- No Diesel Exhaust Fluid tank!

1. Diesel + O2 →Ketone + ‘some’ heat
2. Ketone → Products + heat



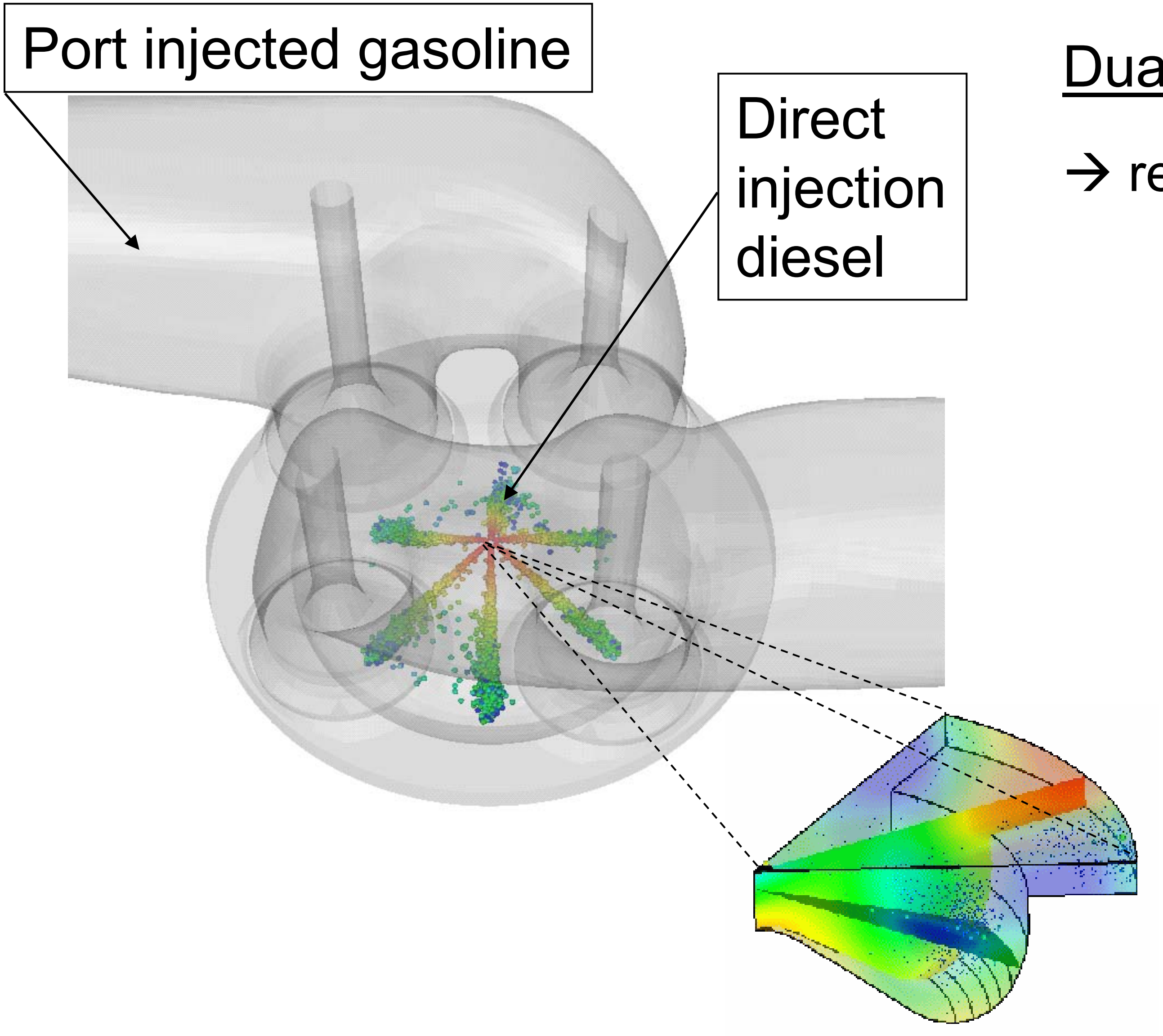
Fuel effects on ignition delay time – charge preparation

Adding varying amounts of gasoline to diesel could help control ignition time



SENKIN Predictions (ERC PRF chemistry mechanism): P_o= 70 bar, Φ= 0.5

CFD used for charge preparation optimization



Port injected gasoline

Direct injection diesel

Dual fuel operation

→ reactivity stratification

Simulation tools

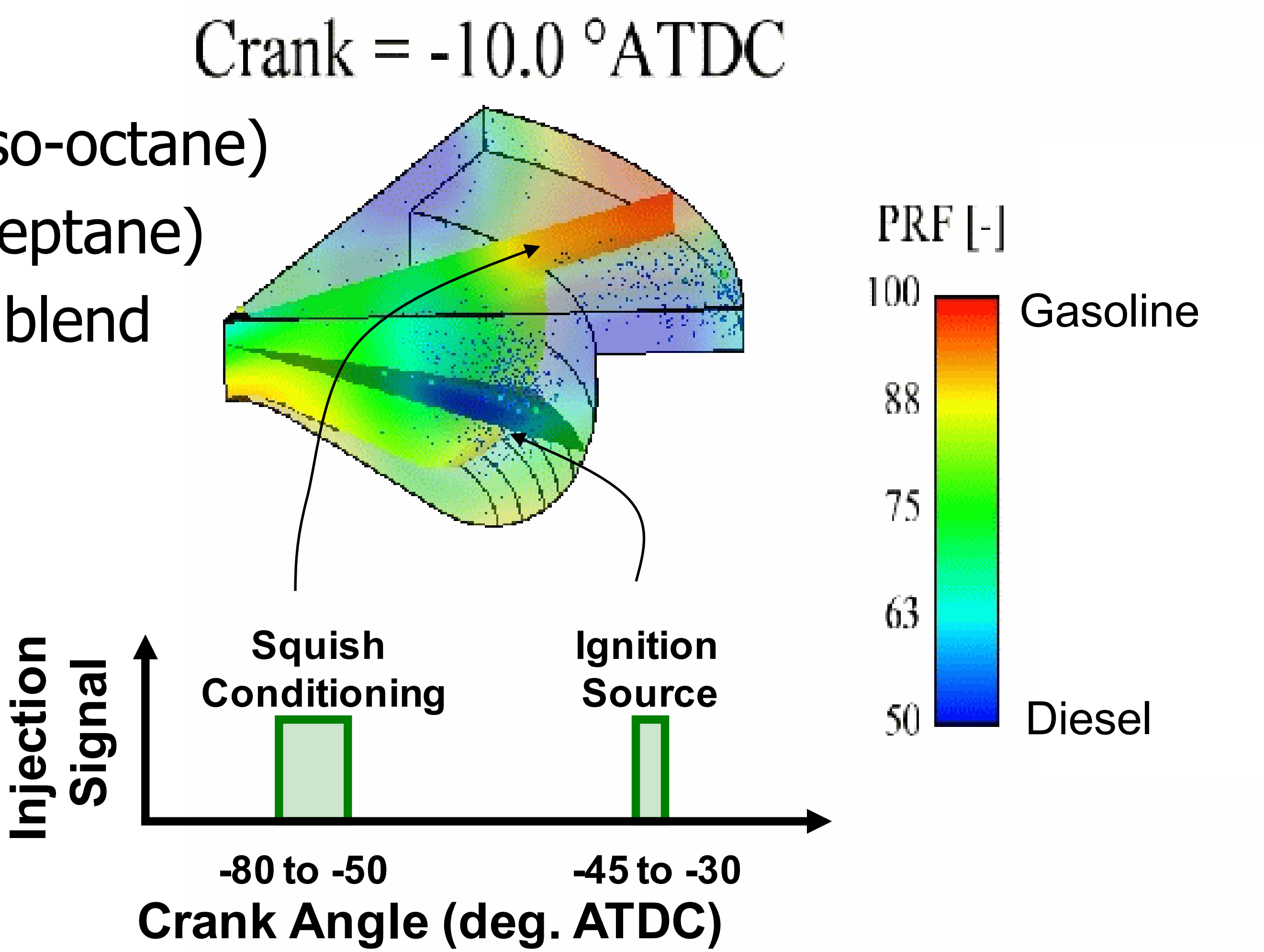
- KIVA-3V CFD code
- ERC grid independent spray models
- ERC PRF chemistry mechanisms* (~44 species, 130 react)
- Multi-objective Genetic Algorithm optimization NSGA-II
- UW CONDOR 4,000 computer pool

* Ra and Reitz, Combustion & Flame, In press., 2010

RCCI dual fuel – port gasoline, direct diesel injection

KIVA CFD plus Genetic Algorithm optimization used to choose injection parameters*

- Red: Gasoline (Iso-octane)
- Blue: Diesel (n-heptane)
- Green: optimum blend

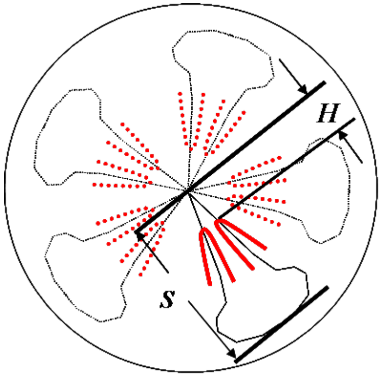


80% gasoline/20% diesel
- SOI1 ~ -60° ATDC
- SOI2 ~ -33° ATDC
- 60% of diesel fuel in first injection

* Kokjohn et al.
SAE 2009-01-2647

Heavy- and light-duty experimental diesel 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

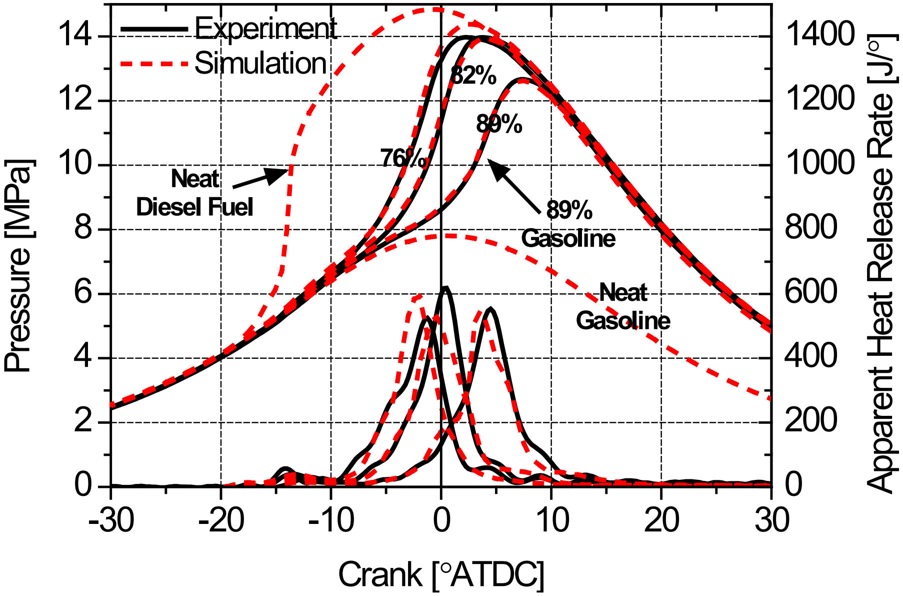


Engine size scaling
Staples et al.
SAE 2009-01-1124

RCCI Experimental Validation - ERC 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 et al.
SAE 2010-01-0864

- **Computer 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 Experimental Validation - ERC Caterpillar SCOTE

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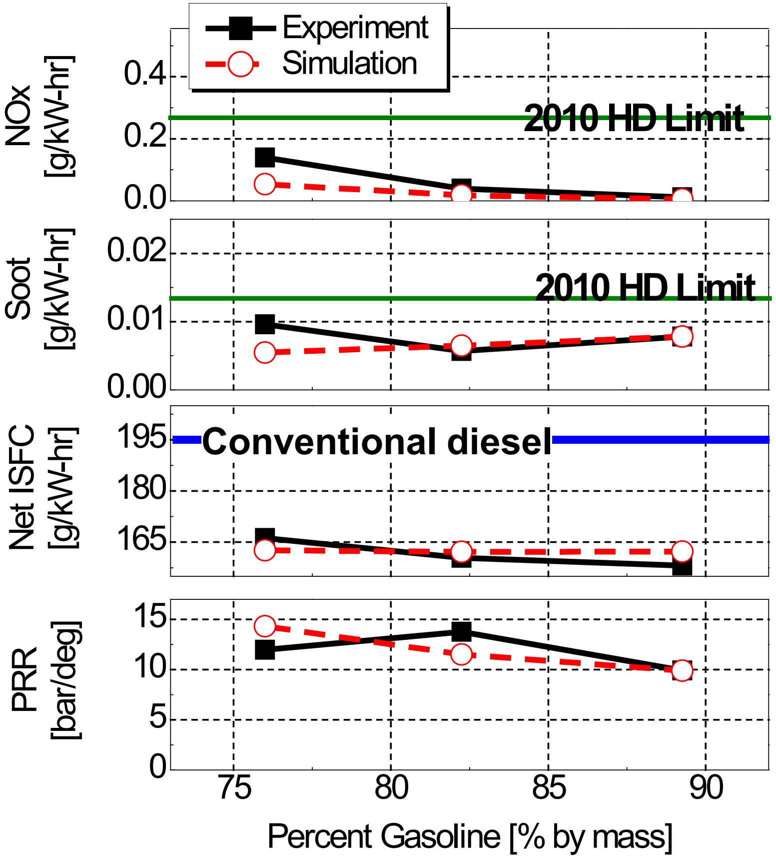
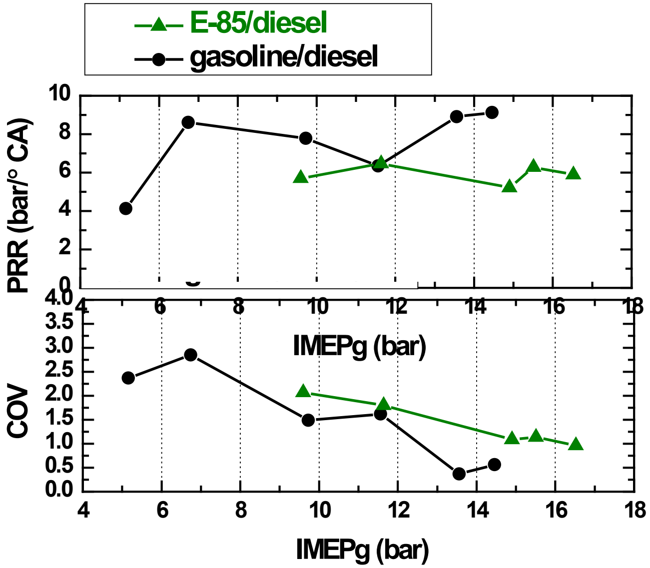
- PRR < 10 bar/deg and net ISFC of **158 g/kW-hr!**

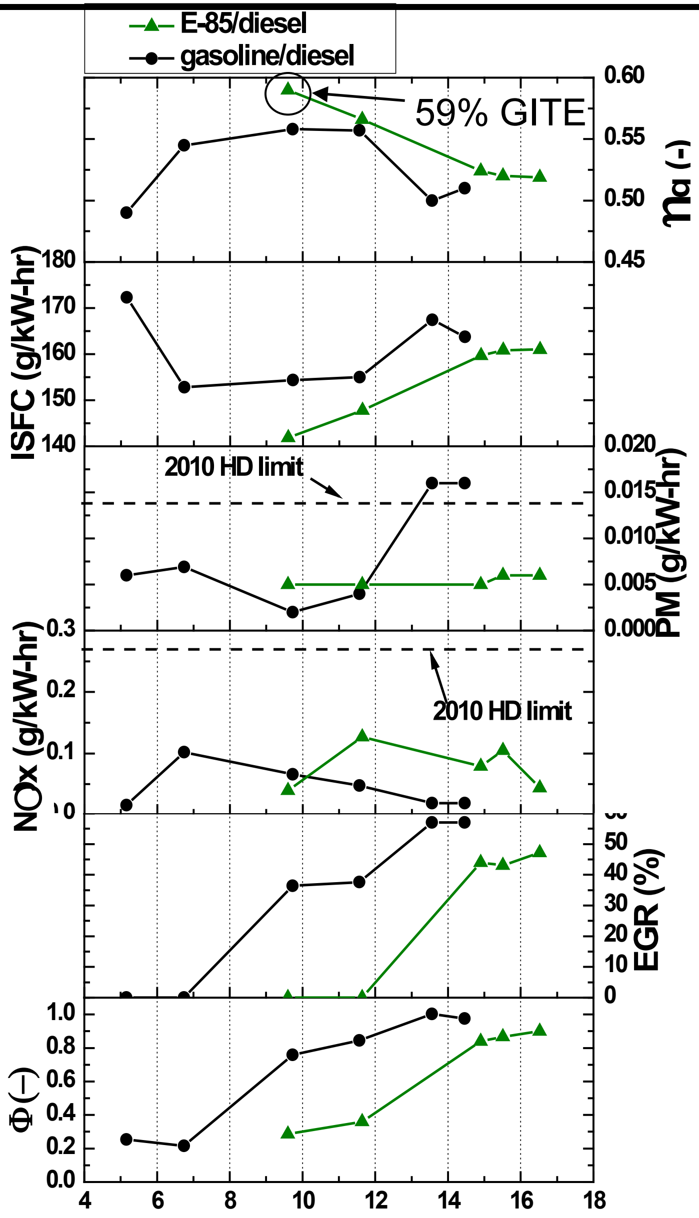


Not only improved fuel efficiency - **ALSO** NOx & soot below EPA 2010!
No exhaust after-treatment required

Load sweep - gasoline/diesel and E85/diesel*

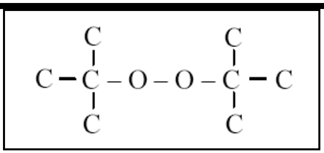
- Use any two fuels with different reactivities
- US EPA 2010 HD emissions met in-cylinder without after-treatment, while achieving ~53-59% thermal efficiency
- Stable combustion and phasing control at both high and low engine loads with PRR < 10 bar/deg.





* 9 bar optimum injection parameters used
Splitter et al. THIESEL, 2010

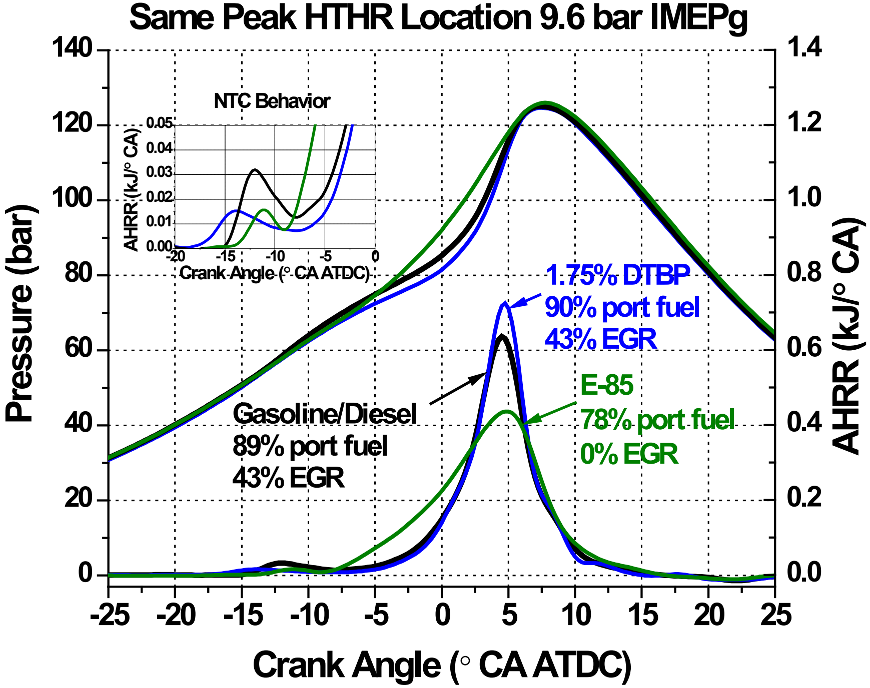
Effect of fuel - RCCI GDI engine? Additized gasoline*

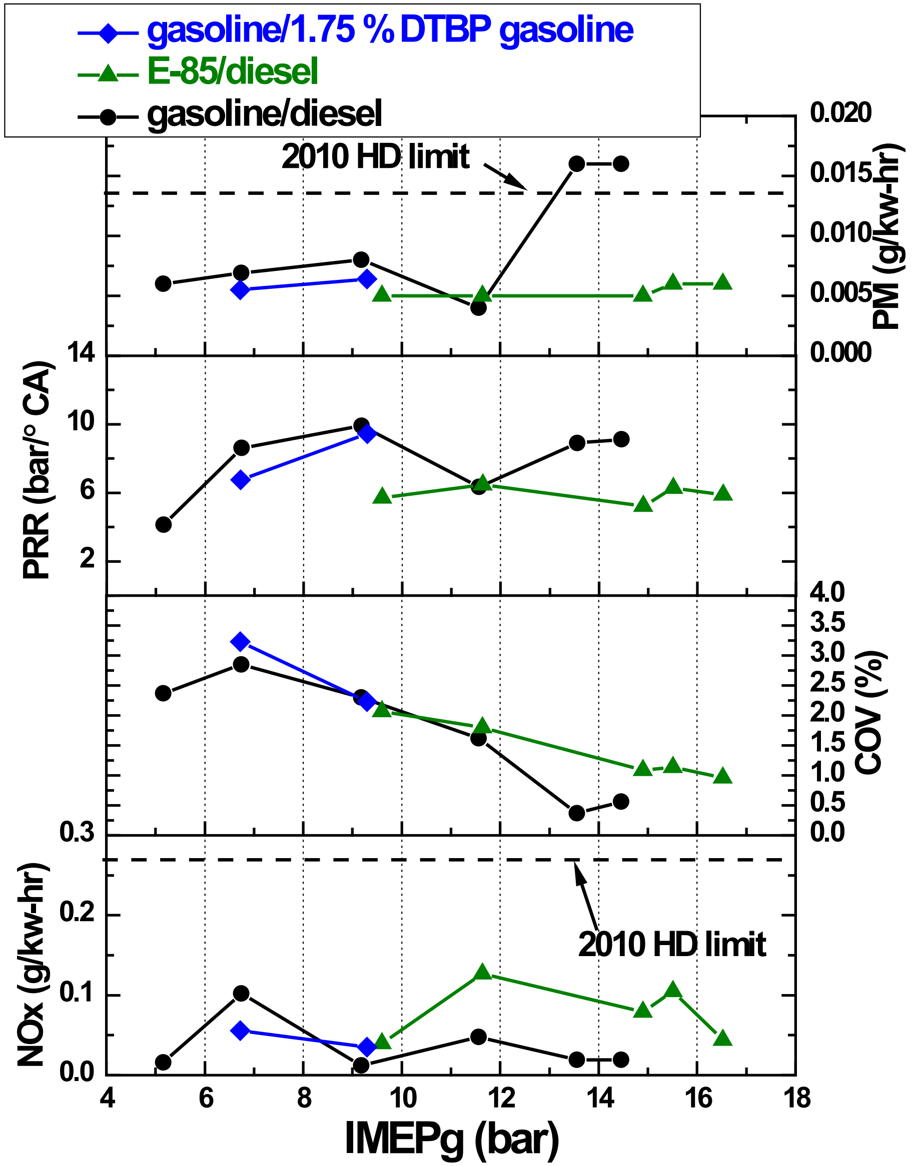


$$\mathrm{C-\overset{C}{\underset{C}{C}}-O-O-\overset{C}{\underset{C}{C}}-C}$$

DI gasoline w/ cetane improver

DTBP: di-tert-butyl peroxide





- Engine does not run without DTBP
- DI gasoline plus 1.75% additive same performance as DI diesel

  → <u>DTBP dosing ~0.2% of total fuel rate</u>
- NOx, soot below EPA 2010
- ISFC 145 g/kW-hr, 56% TE

* Splitter et al. 2010-01-2167

Summary and Conclusions

- An optimized dual-fuel PCCI concept, RCCI, is proposed
- Port fuel injection of gasoline (cost effective)
  Direct injection of diesel or additized gasoline (low injection pressure). Diesel or GDI (w/spark plug) operation retained.
- RCCI engine experiments performed in HD and LD engines
- Near zero NOx and soot achieved in-cylinder in both engines
- High efficiency achieved in both engines (>50% TE)
  - However, heavy-duty engine has ~5% greater thermal efficiency
- Thermal efficiency improved via reduction in heat transfer losses and improvements in combustion phasing
- RCCI technology provides practical low-cost pathway to >20% improved fuel efficiency (lower CO_2), while meeting emissions mandates in-cylinder