Comparison of Conventional Diesel and Reactivity Controlled Compression Ignition (RCCI) Combustion in a Light-Duty Engine

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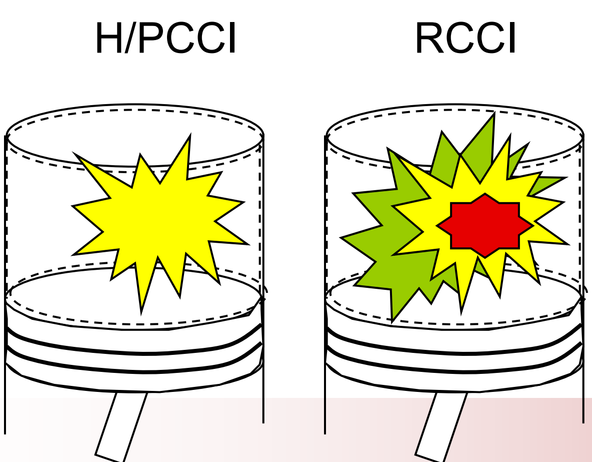
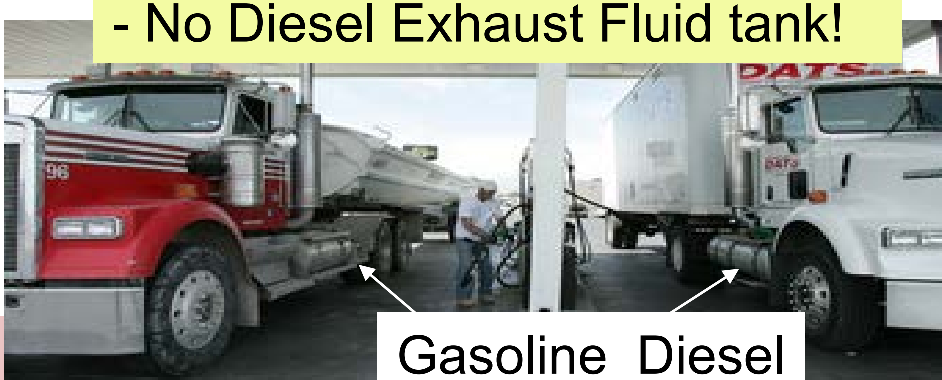
Direct-injection Engine Research Consortium

Reactivity Controlled Compression Ignition - RCCI

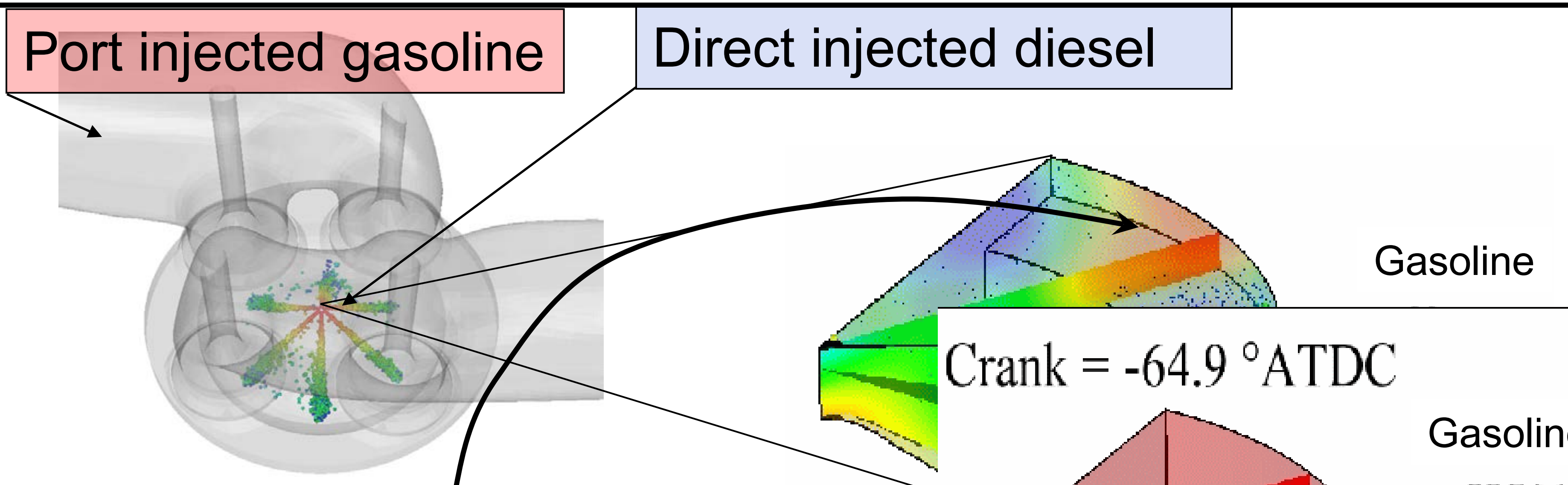
- HCCI Combustion offers high efficiency & low PM and NOx emissions, but is sensitive to fuel properties, is limited to low load and has no direct means to control combustion phasing
- Control can be provided by varying fuel reactivity using **TWO** fuels with different reactivities - dual-fuel PCCI = RCCI:
  - **Port fuel injection of gasoline** (mixed with intake air, as in spark-ignition engines)
  - **Multiple direct-injections of diesel fuel** into combustion chamber later during compression (as in diesel engines)
  - **Optimized fuel blending in-cylinder**

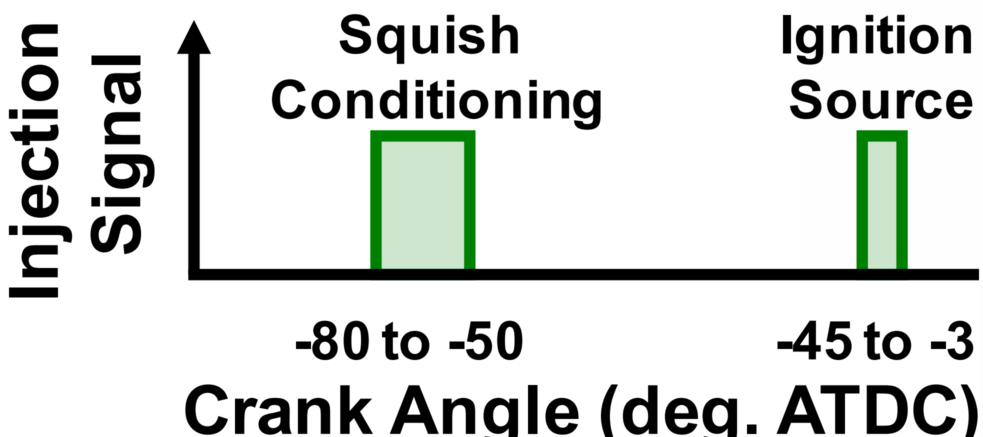


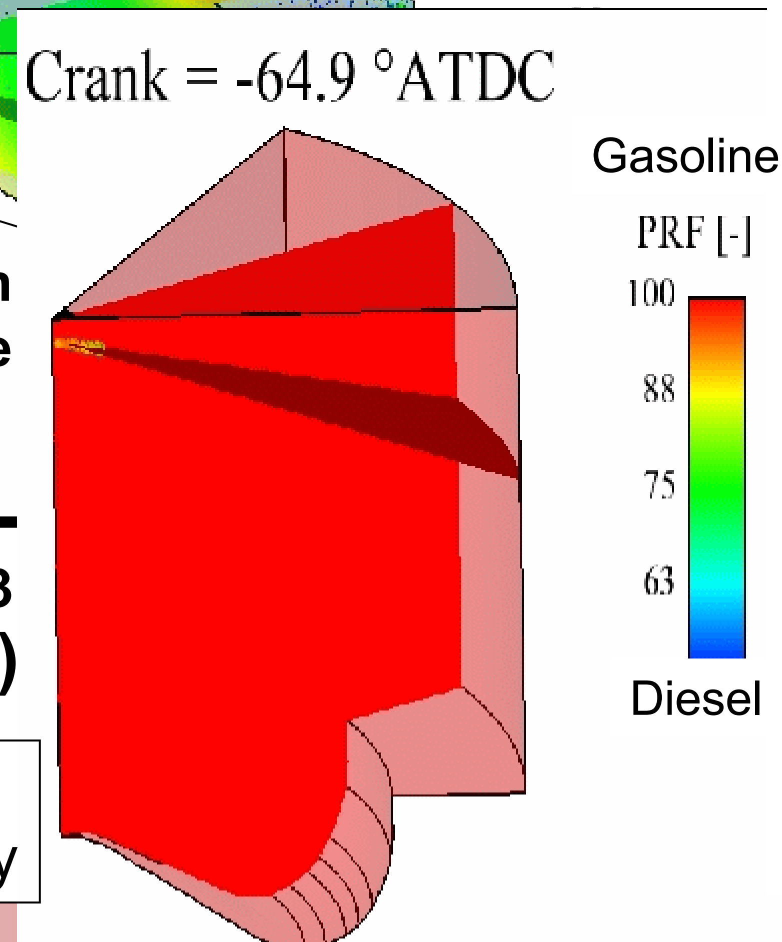
- Emissions regs. met in-cylinder
- No Diesel Exhaust Fluid tank!



Optimized Reactivity Controlled Compression Ignition





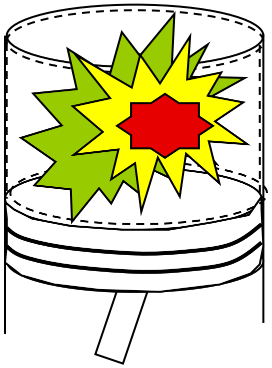


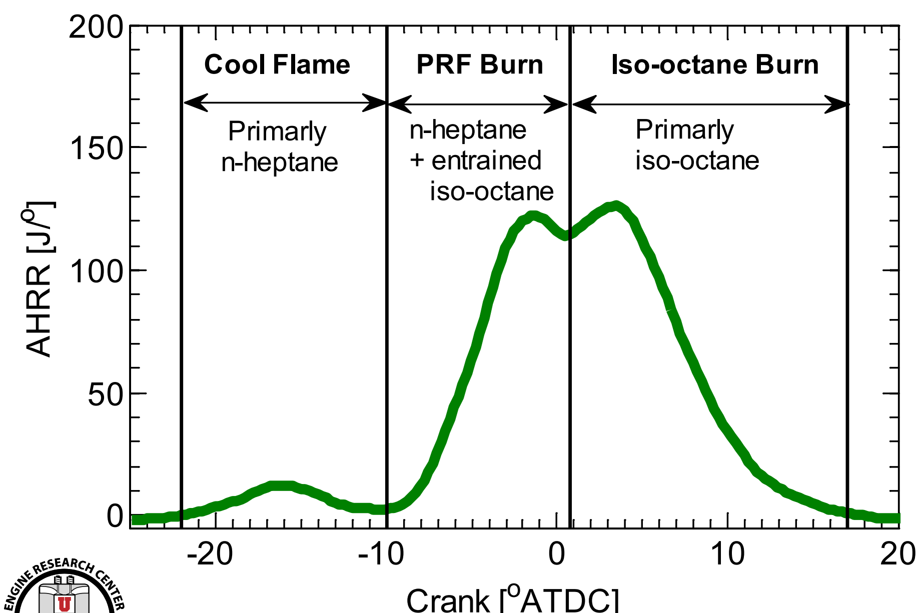
CFD plus Genetic Algorithms used to optimize multiple injection strategy

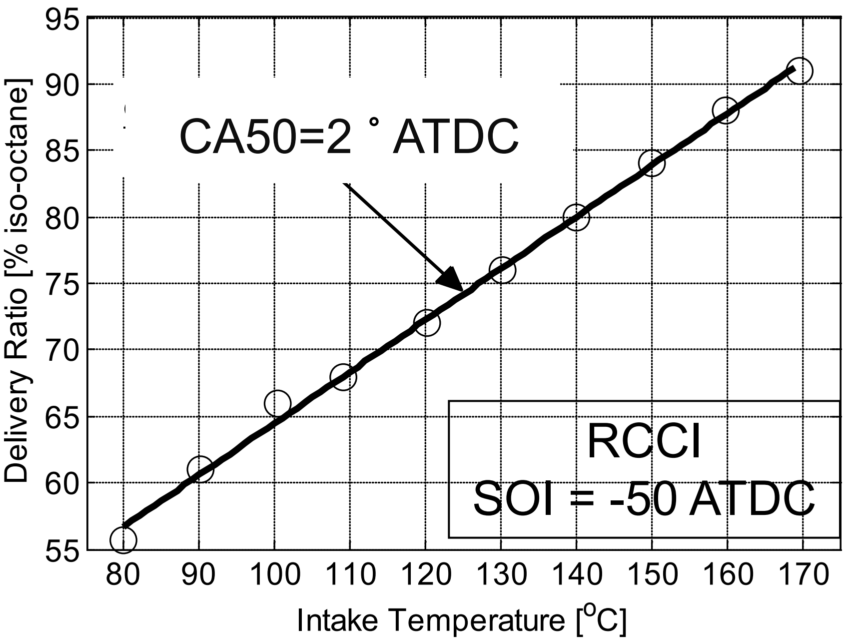
Dual fuel RCCI combustion – controlled HCCI

Kokjohn, IJER 2011

- Heat release occurs in 3 stages
- Cool flame reactions from diesel (n-heptane) injection
- First energy release where both fuels are mixed
- Final energy release where lower reactivity fuel is located
- Changing fuel ratios changes relative magnitudes of stages
- Fueling ratio provides "next cycle" CA50 transient control





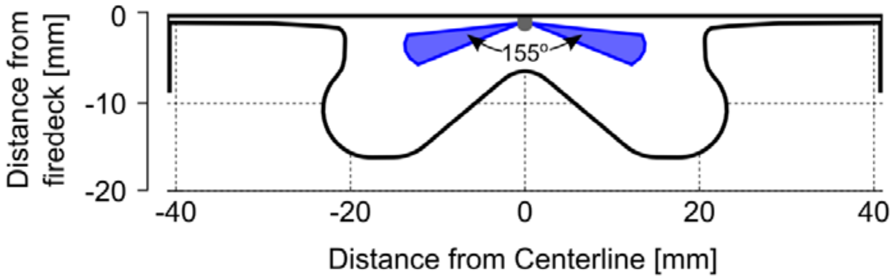


Light-duty automotive drive-cycle performance

Kokjohn, PhD thesis 2012

- Compare conventional diesel combustion (CDC) and Reactivity Controlled Compression Ignition (RCCI) combustion
- Same operating conditions
  (CR, boost, IMT, swirl..)
- ERC KIVA-Chemkin Code
  - Reduced PRF model for diesel and gasoline kinetics
  - Improved ERC spray models

Combustion chamber geometry



Engine specifications

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

Diesel fuel injector specifications

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

Comparison between RCCI and Conventional Diesel

- Five operating points of Ad-hoc fuels working group
- Tier 2 bin 5 NOx targets from:

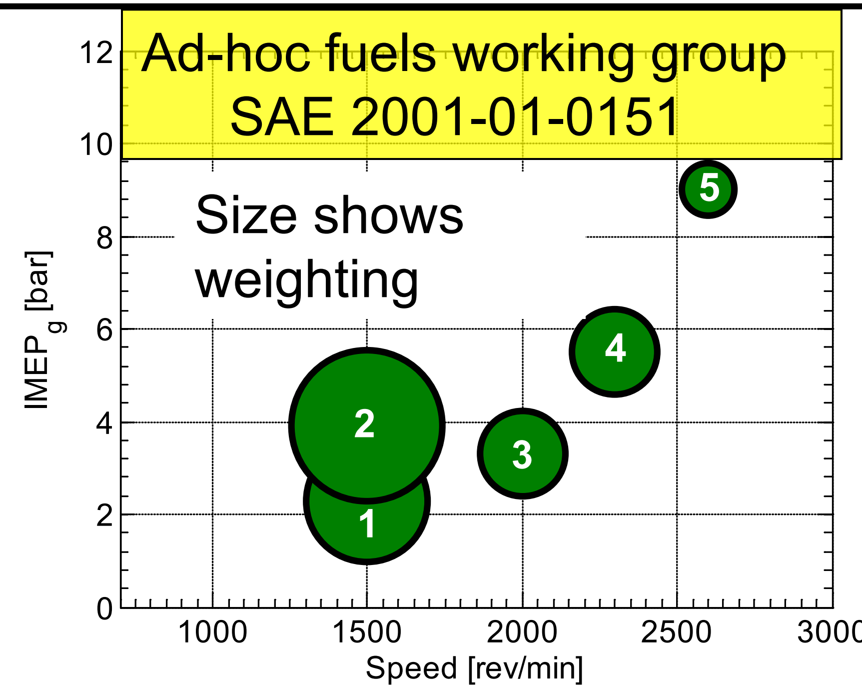
  Cooper, SAE 2006-01-1145

  (assumes 3500lb Passenger Car)
- Evaluate NOx / fuel efficiency tradeoff using SCR for CDC

<u>Assumptions</u>

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

  Johnson, SAE 2011-01-0304
- No DPF regeneration penalty
- UHC and CO only lead to reduced work

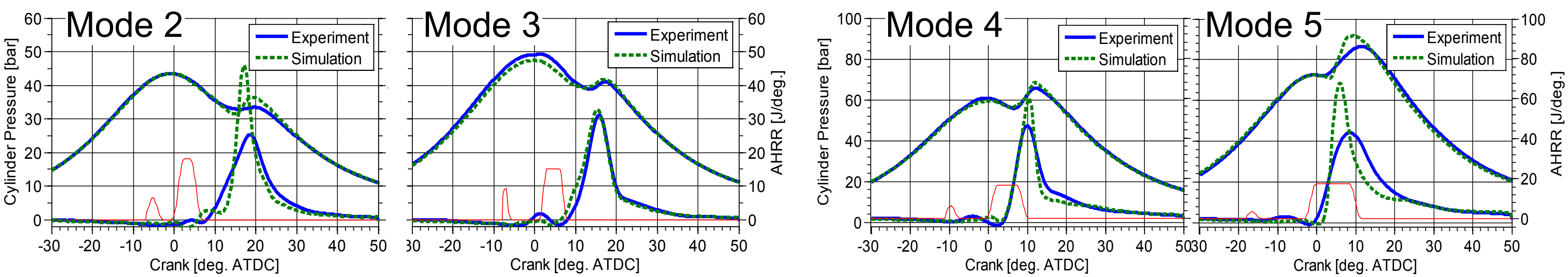


Mode	Speed (rpm)	IMEP (bar)	CDC Baseline NOx (g/kgf) *	NOx Target (g/kgf)
1	1500	2	1.3	0.2
2	1500	3.9	0.9	0.4
3	2000	3.3	1.1	0.3
4	2300	5.5	8.4	0.6
5	2600	9	17.2	1.2

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

Euro 4 operating conditions - Conventional Diesel

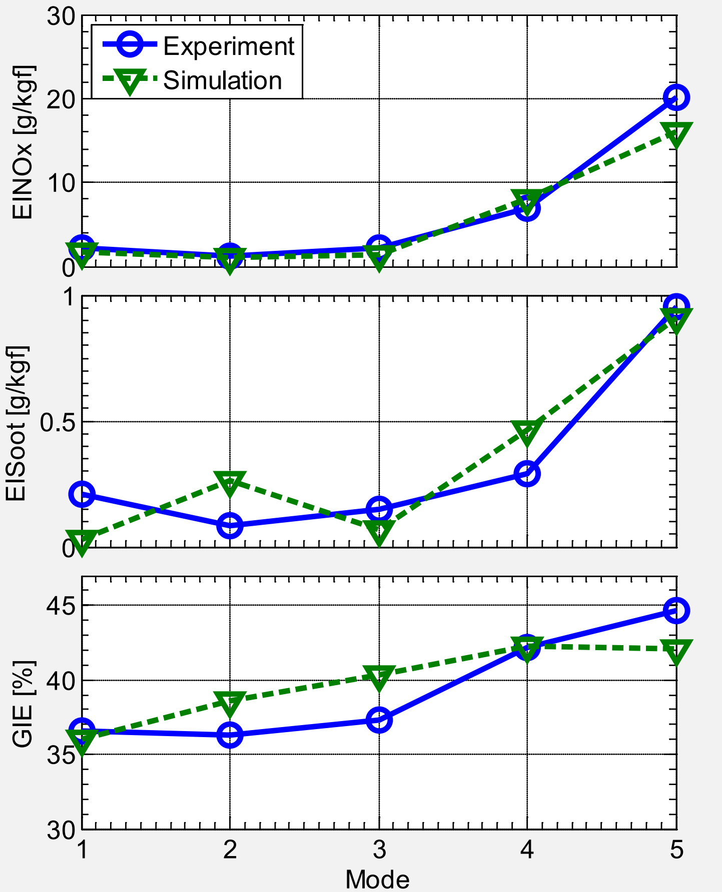
Model validation	**CDC Operating Conditions ***				
Mode	1	2	3	4	5
IMEPg (bar)	2.3	3.9	3.3	5.5	9
Speed (rev/min)	1500	1500	2000	2300	2600
Total Fuel (mg/inj)	5.6	9.5	8	13.3	20.9
Intake Temp. (C)	60	60	70	67	64
Intake Press. (bar abs)	1	1	1	1.3	1.6
EGR Rate (%)	47	38	42	25	15
CR Inj. Pressure (bar)	330	400	500	780	1100
Pilot SOI (° ATDC)	-5.8	-7.2	-8.2	-11.7	-15.4
Main SOI (° ATDC)	1.6	0	1.6	-0.1	-2.6
DI fuel in Pilot (%)	34	16	15	10	5



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

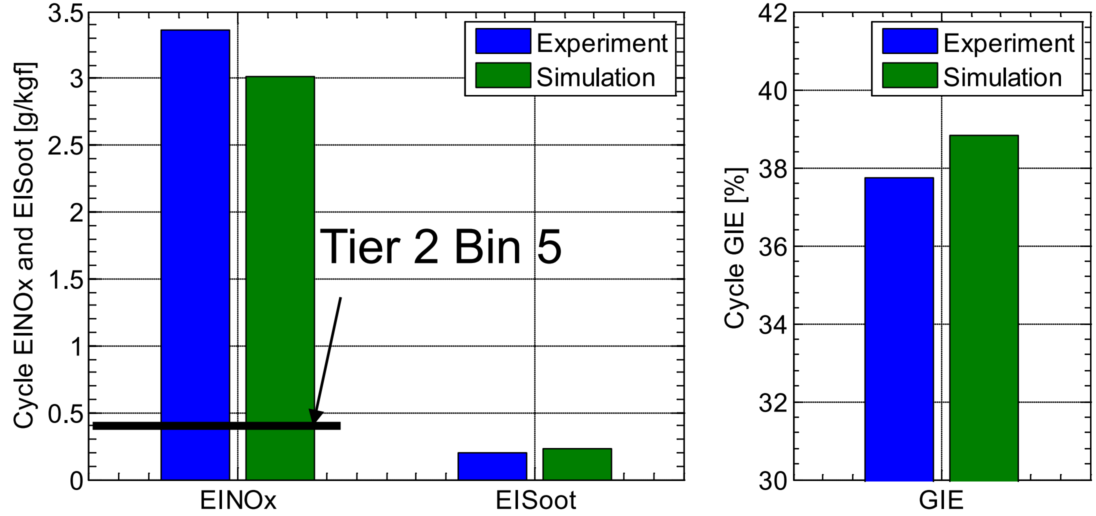
Model Validation (Euro 4)

Comparison at 5 Modes

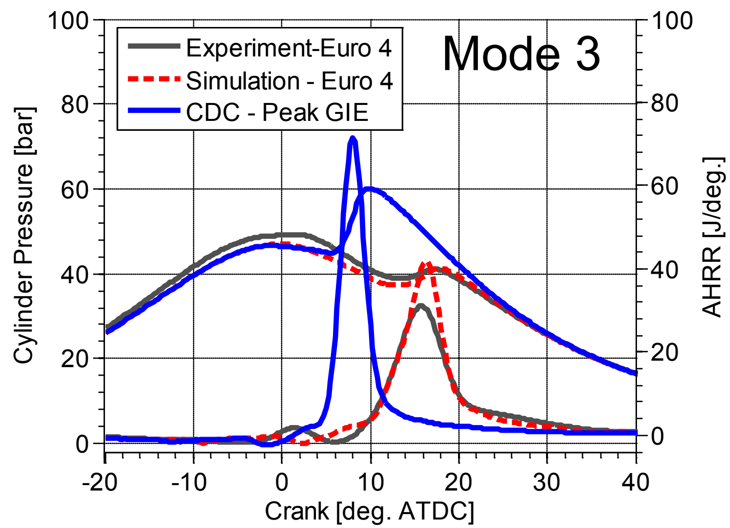


Weighted average: $$E_{cycle} = \frac{\sum_{imode=1}^{5} E_{imode} Weight_{imode}}{\sum_{imode=1}^{5} Weight_{imode}}$$

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

Comparison between RCCI and CDC plus SCR

CDC (with SCR)

- Main injection timing swept

DEF consumption 1% per 1 g/kW-hr reduction in NOx

$$GIE_{Total} = \frac{Work_{-180\text{ to }180}}{(m_{DEF} + m_{Fuel}) * LHV_{Fuel}} \times 100$$

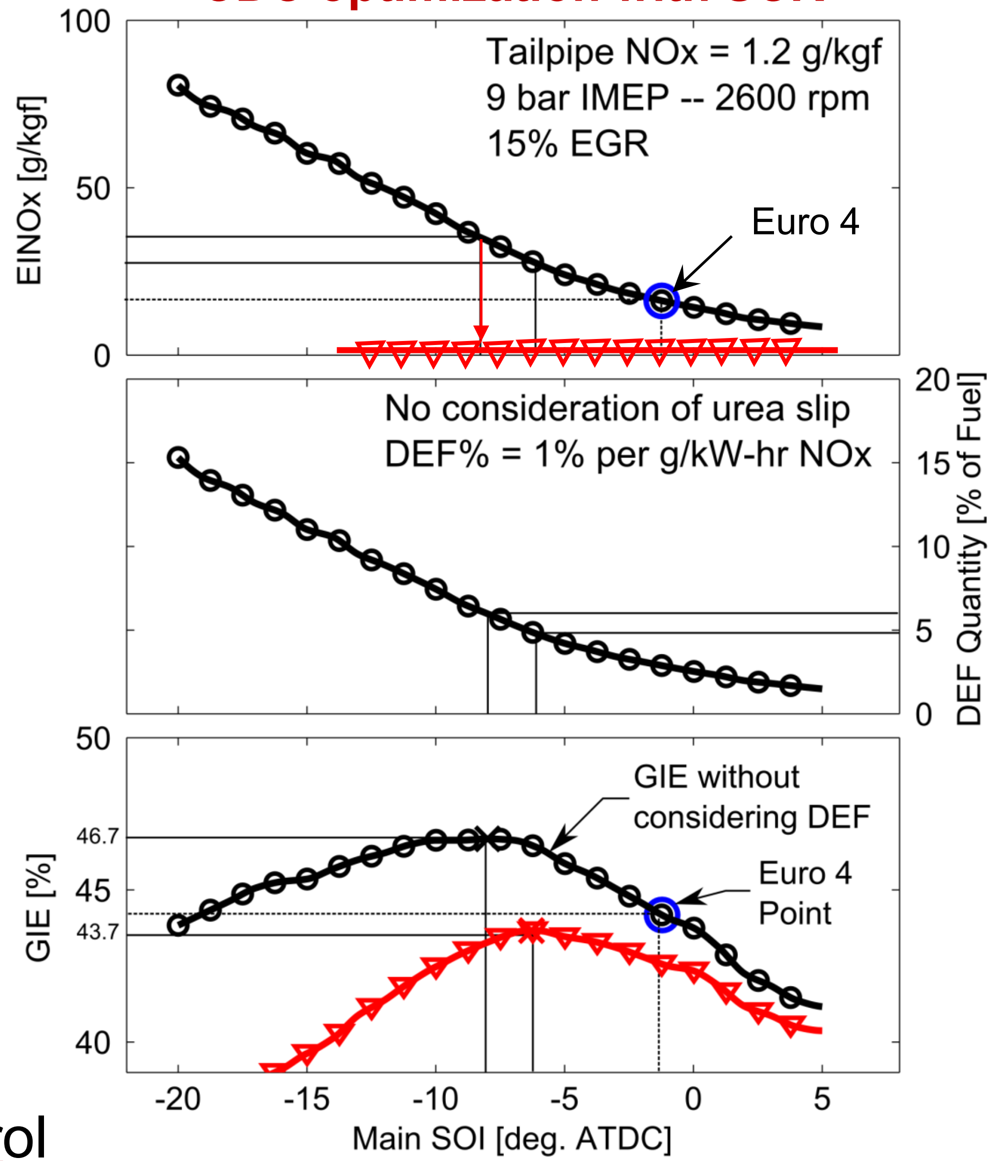
- Peak efficiency at tradeoff between fuel consumption (SOI timing) and DEF consumption (engine-out NOx)

RCCI (No SCR needed)

Gasoline amount controls CA50 to meet NOx/PRR constraints

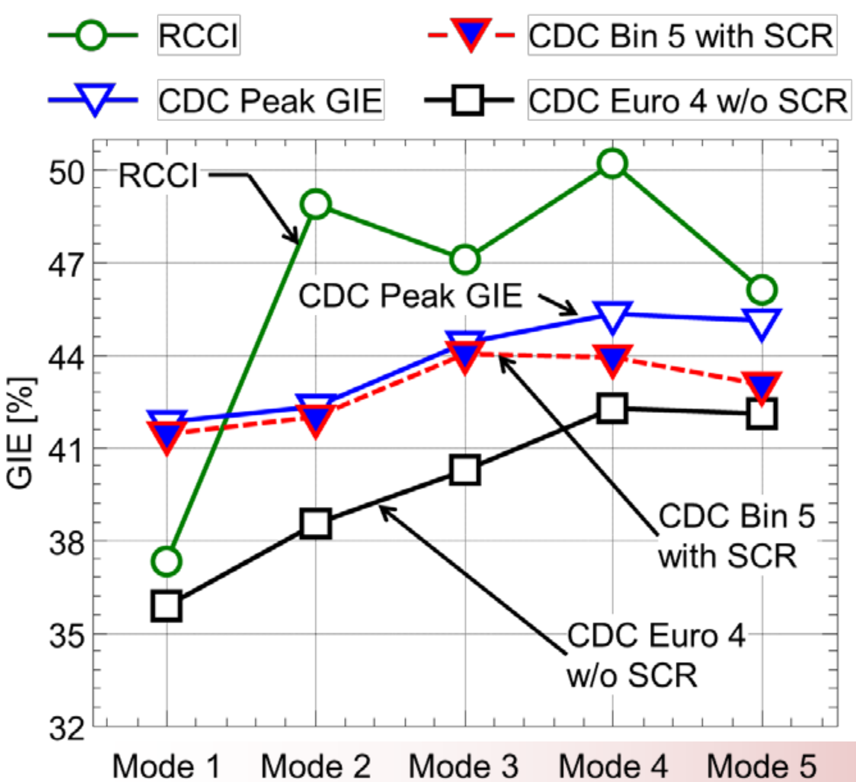
Mode 1 uses diesel LTC (no gasoline and EGR)

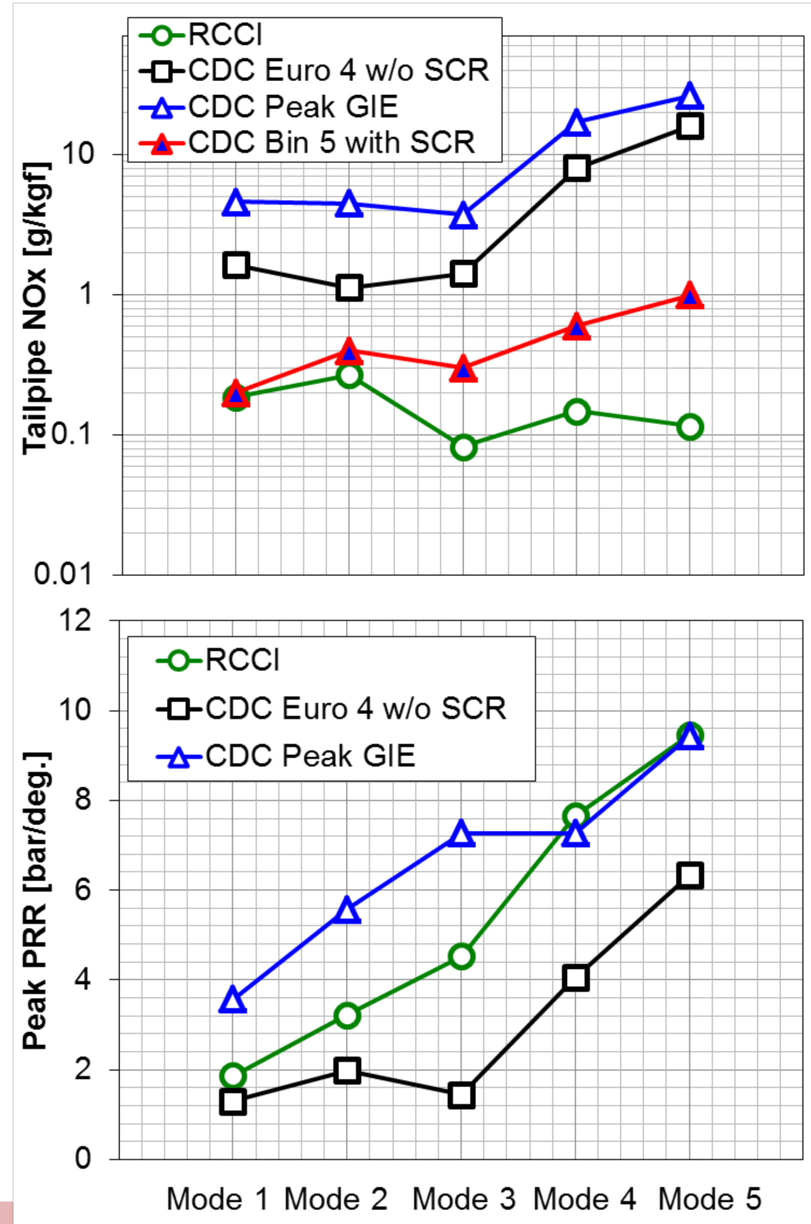
Mode 5 has EGR for CA50 control



Comparison of Efficiency, NOx and PRR

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

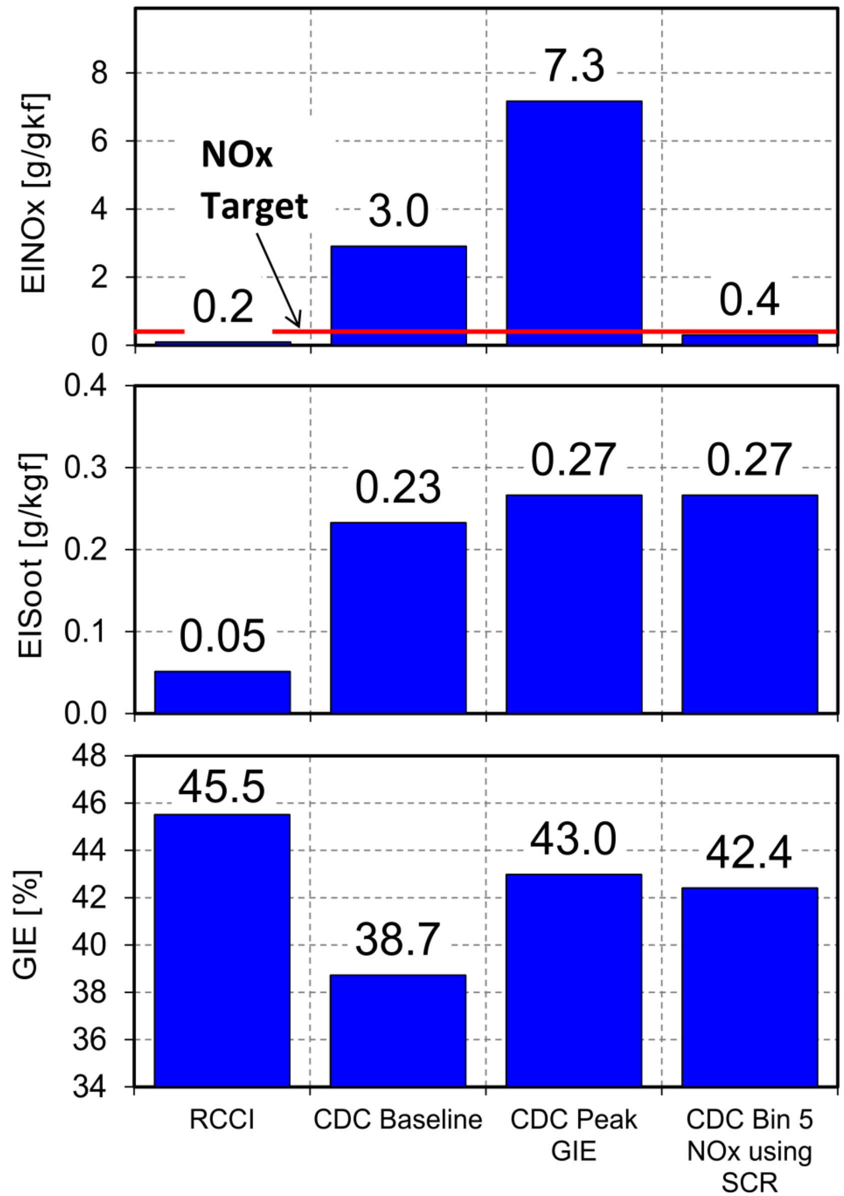




Cycle averaged NOx, Soot and GIE

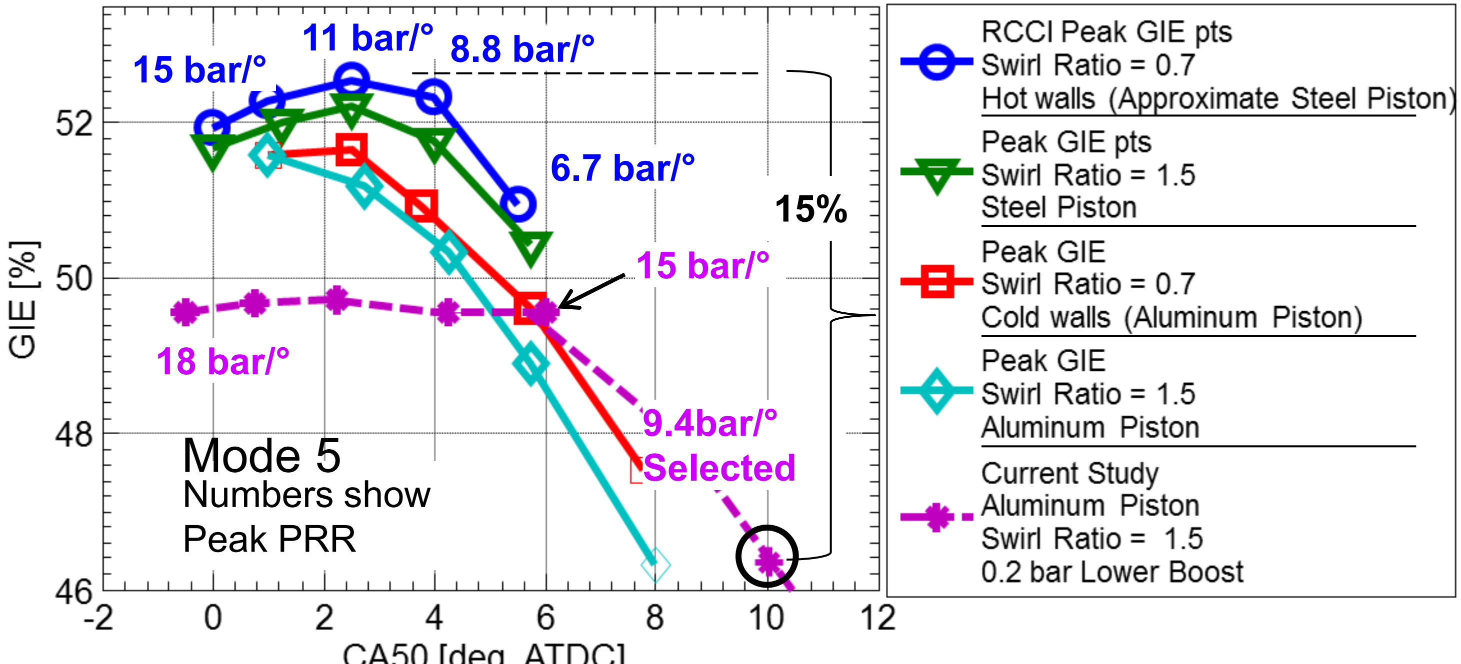
- RCCI and CDC compared at baseline and Tier 2 Bin 5 NOx
- CDC NOx-GIE tradeoff controlled by main injection timing
- RCCI meets NOx targets without after-treatment
- RCCI gives ~7% improvement in fuel consumption over CDC+SCR
- RCCI soot is an order of magnitude lower than CDC+SCR
- RCCI HC is ~5 times higher than CDC+SCR
- Crevice-originated HC emissions

Splitter, SAE 2012-01-0383



Future research directions

- LD RCCI improved by relaxing constraints (Euro 4 boost, IMT, swirl..)
- Peak efficiency at Mode 5 is 46.1% → CFD predicts increase to ~53%
  – 7% + 15% ~ DOE goals of 20-40% improvement
  – Higher boost (1.86 bar vs. 1.6 bar) allows CA50 advance with same PRR, lowers heat transfer losses due to lower Φ (lower temps)
  – Lower swirl reduces convective heat transfer losses
  – Higher wall temps improve combustion efficiency (steel piston)



Kokjohn, PhD thesis 2012

Summary and Conclusions

- RCCI yields clean, quiet, and efficient combustion over wide load/speed ranges (HD: 4 to 23 bar IMEP, 800 to 1800 rev/min).

  HD: EPA 2010 NOx/PM emissions met in-cylinder with GIE >55%

  LD: Low NOx and PM emissions with less EGR over FTP cycle.
- Suggested RCCI strategy: Optimized high EGR CDC combustion at low load (idle) and no EGR up to Mode 5 (~9 bar IMEP).
- RCCI LD modeling indicates ~7% improved fuel consumption over CDC+SCR over FTP cycle using same engine/conditions.
- RCCI meets Tier 2 bin 5 without needing NOx after-treatment or DPF, but DOC will likely be needed for UHC reduction
- Further RCCI optimization possible with:

  higher boost pressure, higher piston temps,

  reduced swirl, surface area, optimized crevice
- RCCI experiments/modeling: optimized pistons,

  alternative fuels ….. and vehicle testing!

Comparison between RCCI and Conventional Diesel

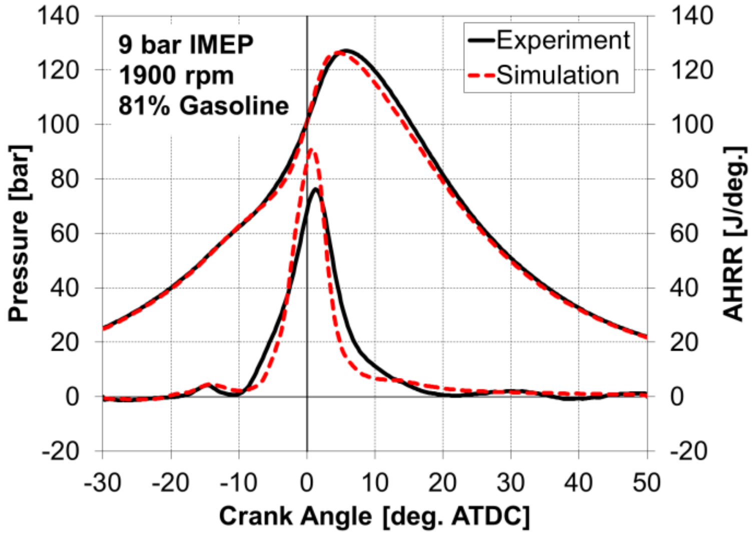
CDC and RCCI efficiency sensitive to selected value of peak PRR

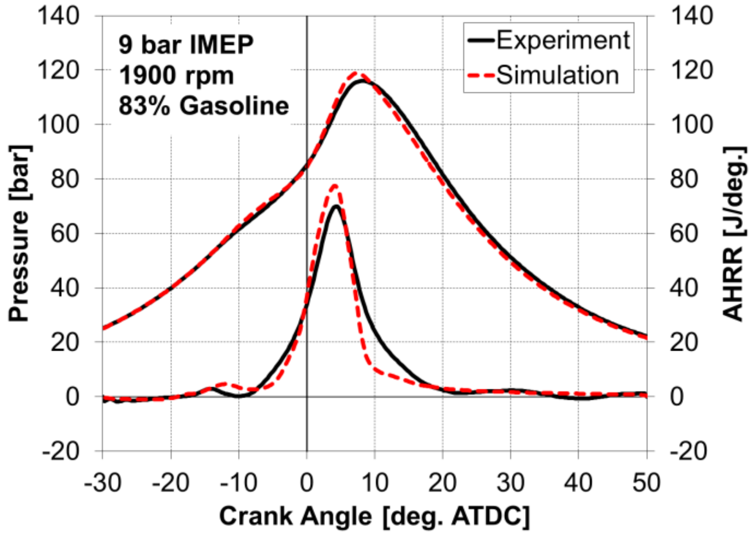
- Maximum allowable PRR of CDC points set at 1.5 times higher than for RCCI

	CDC	RCCI	CDC	RCCI	CDC	RCCI	CDC	RCCI	CDC	RCCI
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	61	38	0	42	0	25	0	15	36
Premixed Gasoline (%)	0	0	0	80	0	55	0	80	0	89
CR Inj. Pressure (bar)	330	500	400	500	500	500	780	500	1100	500
SOI (° ATDC) Baseline	-5.8/ 1.6	-33/ -8	-7.2/ 0	-58/ -37	-8.2/ 1.6	-58/ -37	11.7/ 0	-58/ -37	-18.6/ -2.6	-58/ -37
SOI (° ATDC) Peak GIE	-14.4/ -6	N/A	-20.2/ -5	N/A	-15.8/ -6	N/A	-17.6/ -6	N/A	-23/ -7	N/A
Percent of DI fuel in Pilot	20	42	15	60	15	60	10	0	10	60
DEF (%)	0.9	0	0.8	0	0.7	0	3	0	4.6	0

RCCI Model Validation

Kokjohn et al. SAE 2011-01-0375





IMEPg (bar)	9
Speed (rev/min)	1900
Total Fuel (mg/inj.)	20
Intake Temp. (deg. C)	36
Intake Press. (bar abs.)	1.86
EGR Rate (%)	41
CR Inj. Pressure (bar)	500
Pilot SOI (° CA) (actual)	-56
Main SOI (° ATDC) (actual)	-35
Percent of DI fuel in Pilot (%)	60%