Reciprocating Internal Combustion Engines

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Summer School on Combustion
Course Length: 15 hrs

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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)
- Part 1: IC Engine Review, 0, 1 and 3-D modeling
- Part 2: Turbochargers, Engine Performance Metrics

Day 2 (Combustion Modeling)
- Part 3: Chemical Kinetics, HCCI & SI Combustion
- Part 4: Heat transfer, NOx and Soot Emissions

Day 3 (Spray Modeling)
- Part 5: Atomization, Drop Breakup/Coalescence
- Part 6: Drop Drag/Wall Impinge/Vaporization/Sprays

Day 4 (Engine Optimization)
- Part 7: Diesel combustion and SI knock modeling
- Part 8: Optimization and Low Temperature Combustion

Day 5 (Applications and the Future)
- Part 9: Fuels, After-treatment and Controls
- Part 10: Vehicle Applications, Future of IC Engines

Tamagna, 2007
Dempsey, 2014

Fuels & advanced combustion strategies

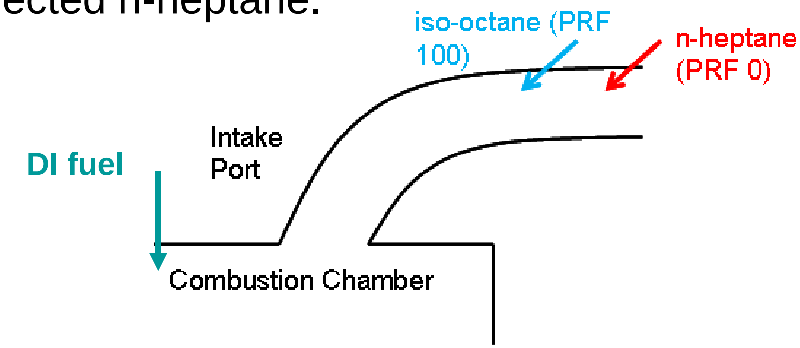
Engine	
Base Engine	GM 1.9L Diesel
Geometric Compression Ratio	17.3
Piston Bowl Shape	RCCI
Displacement	0.477 L
Bore/Stroke	82.0 / 90.4 mm
IVC/EVO	-132°/112° ATDC
Swirl Ratio	1.5
Port Fuel Injectors	
Model Number	TFS-89055-1
Inj. Press.	2.5 to 3.5 bar
Rated Flow	25 kg/hr.
Common Rail Injector	
Model	Bosch CRI2.2
Number of Holes	7
Hole Diameter	0.14 mm
Included Angle	148°
Fixed Inj. Press.	**500 bar**

PRF fuels used: **n-heptane & iso-octane**

HCCI: Dual-fuel allows CA50 to be varied with fixed intake temperature.

PPC: A gasoline-like reactivity of PRF 94 chosen for both port injection and direct injection – i.e., single fuel PPC.

RCCI: Port injected neat iso-octane and direct injected n-heptane.



Fuel Injector	**HCCI**	**PPC**	**RCCI**
Port Injector #1	PRF 75	PRF 94	PRF 100
Port Injector #2	PRF 100	PRF 94	PRF 100
DI Injector	-	PRF 94	PRF 0

Controllability of advanced combustion strategies

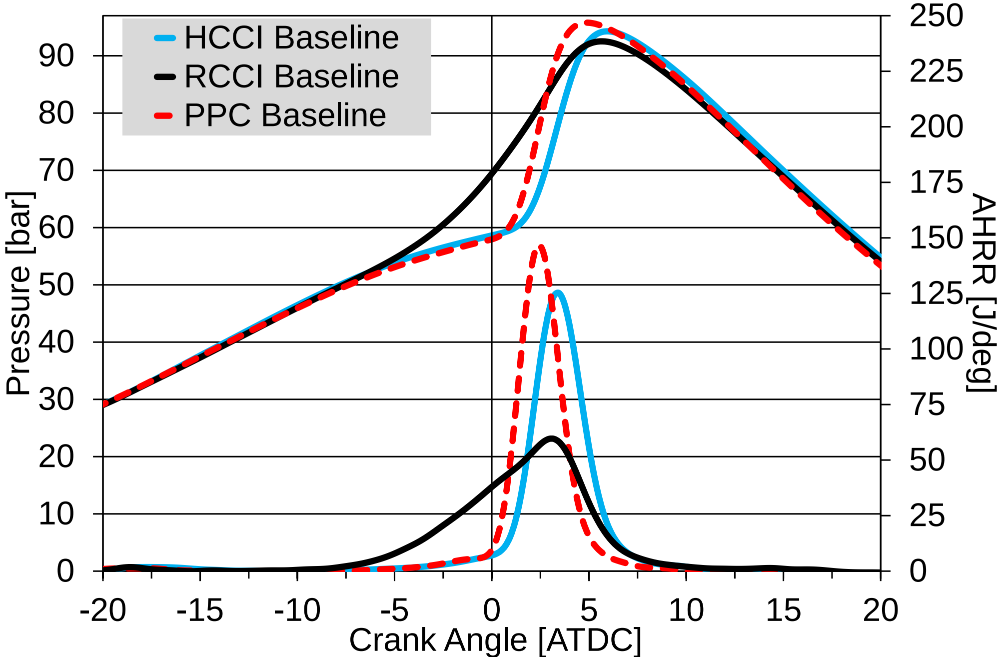
Baseline operating condition

(5.5 bar IMEP & 1500 rev/min**)**

Inputs	**HCCI**	**PPC**	**RCCI**
Pin [bar]	1.3	1.3	1.3
Tin [C]	50	70	50
Premixed Fuel [%]	100%	79.1%	92.6%
Global PRF #	93	94	92.6
DI Timing [°ATDC]	-	-65°	-45°
Global Phi	0.33	0.34	0.33
Results	**HCCI**	**PPC**	**RCCI**
CA50 [°ATDC]	3.5	2.5	2.2
Gross Ind. Eff. [%]	**47.1%**	**45.6%**	**47.5%**
Comb. Eff. [%]	92.8%	93.1%	91.5%
NOx [g/kg-fuel]	**<0.05**	**<0.05**	**<0.05**
PPRR [bar/°]	14	16	5.8

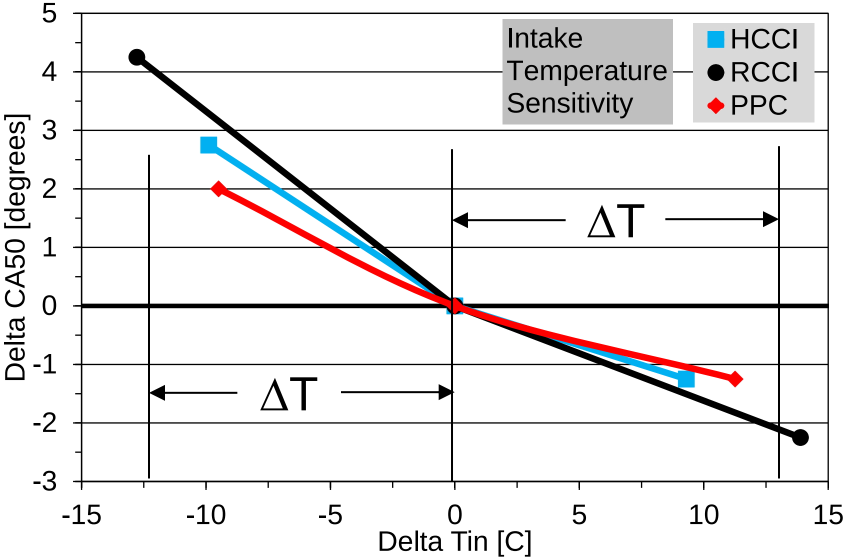
- Single DI injections for PPC & RCCI
- Ultra-low NOx emissions and high GIE
- RCCI has highest GIE, but lowest η_{comb}, suggesting lower HT losses (lower PPRR)
- Fuel stratification with PPC results in higher PPRR compared to HCCI

(c.f., Dec et al. 2011 low intake pressure (< 2 bar))



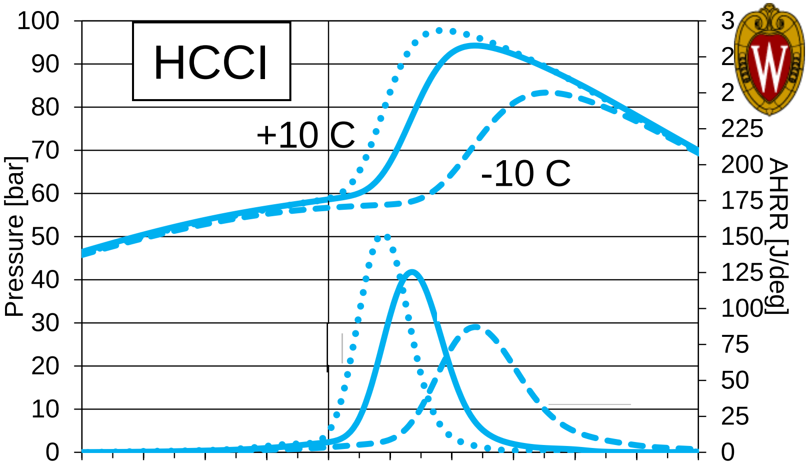
Sensitivity to intake temperature

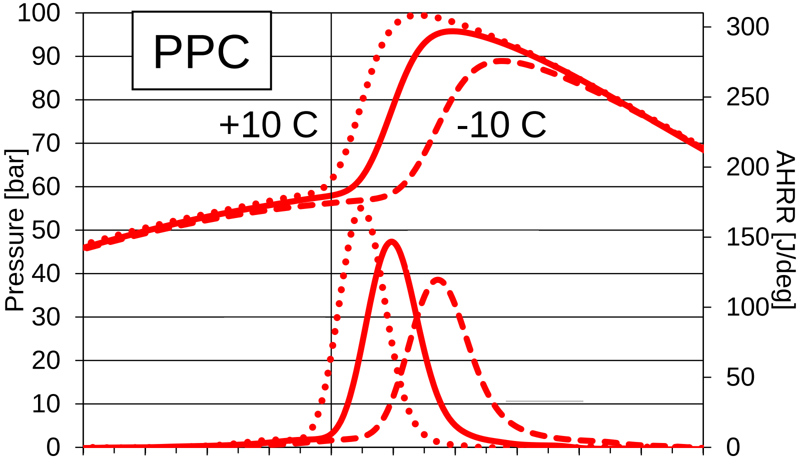
- Each strategy is predominantly controlled by chemical kinetics → sensitive to temperature

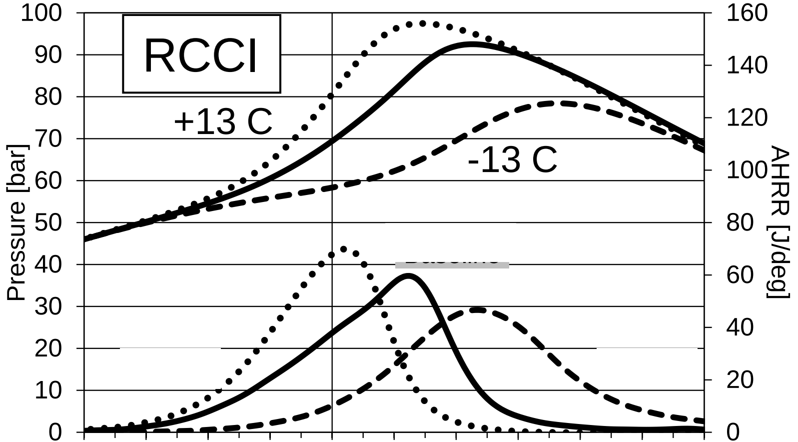


- To assess controllability of strategies, try to recover baseline CA50.
- This demonstrates combustion strategy's ability to be controlled in a real world engine on a cycle-by-cycle basis (i.e., transient operation and unpredictable environmental conditions).

Dempsey, 2014





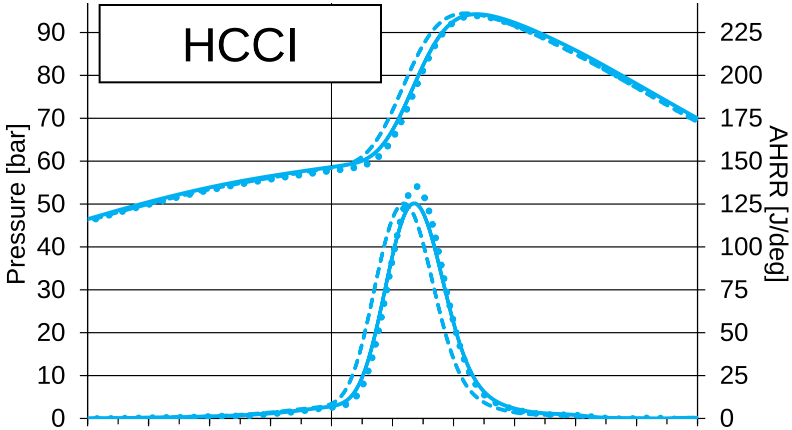


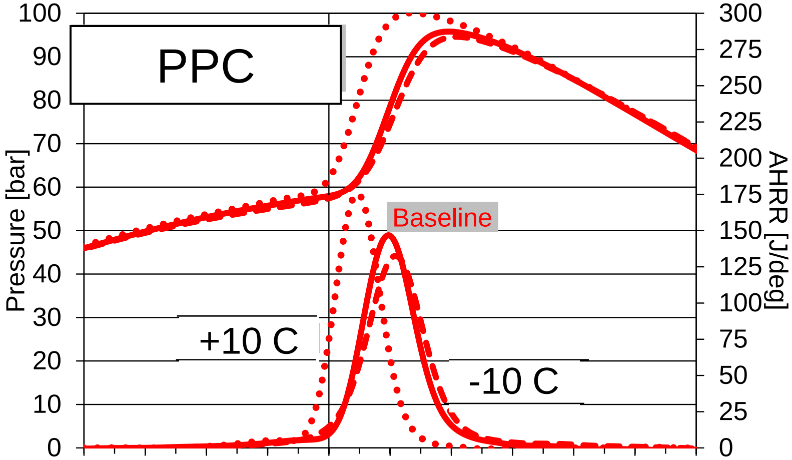
Ability to compensate for ΔT

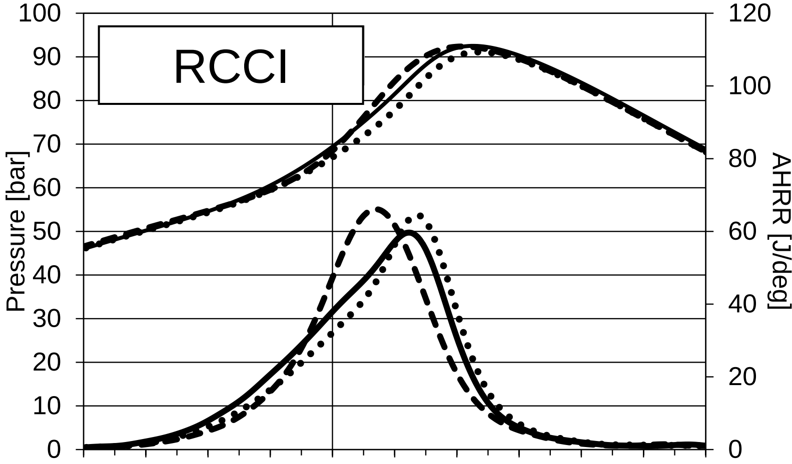
HCCI	-10 C Corrected	Baseline	+10 C Corrected
Global PRF #	91	93	94
CA50 [°ATDC]	3.0	3.5	3.5
NOx [g/kg-fuel]	<0.05	<0.05	<0.05

PPC	-10 C Corrected	Baseline	+10 C Corrected
Premixed Fuel [%]	72.6%	79.1%	95.2%
DI Timing [°ATDC]	-36°	-65°	-65°
CA50 [°ATDC]	3.0	2.5	**1.2**
NOx [g/kg-fuel]	**0.63**	<0.05	<0.05

RCCI	-13 C Corrected	Baseline	+13 C Corrected
Premixed Fuel [%]	89%	92.6%	94%
DI Timing [°ATDC]	-45°	-45°	-45°
CA50 [°ATDC]	1.7	2.2	2.7
NOx [g/kg-fuel]	<0.05	<0.05	<0.05



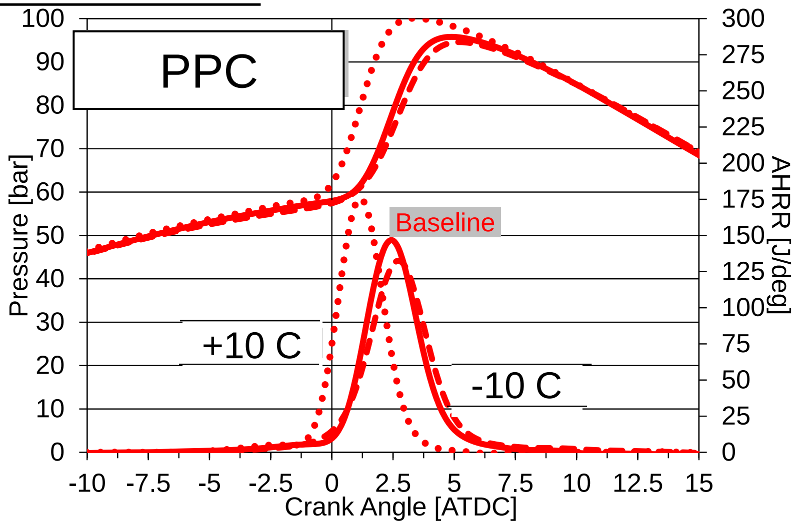


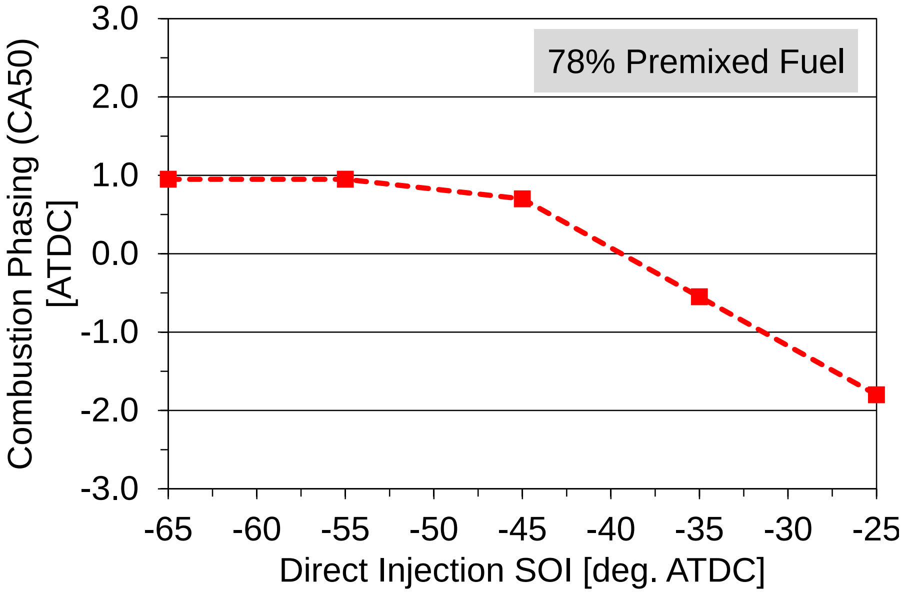


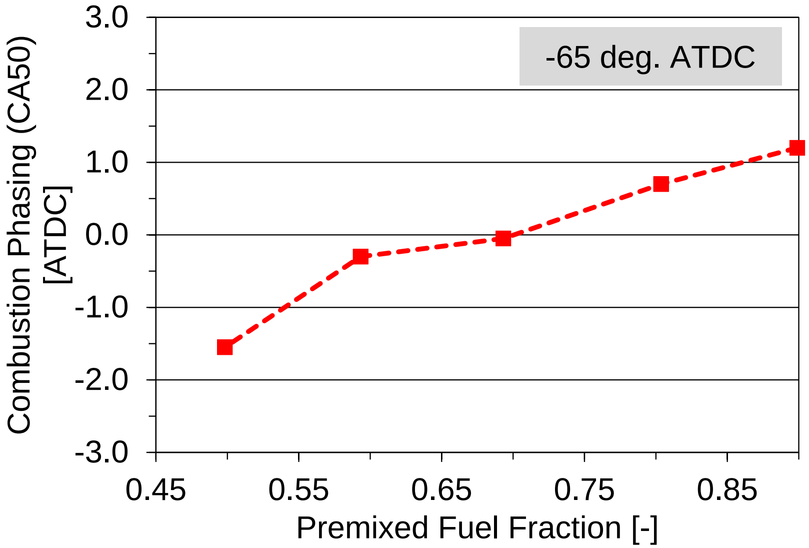
Dempsey, 2014

Ability to compensate for intake temperature – PPC

PPC	-10 C Corrected	Baseline	+10 C Corrected
Premixed Fuel [%]	72.6%	79.1%	95.2%
DI Timing [°ATDC]	-36°	-65°	-65°
CA50 [°ATDC]	3.0	2.5	**1.2**
NOx [g/kg-fuel]	**0.63**	<0.05	<0.05



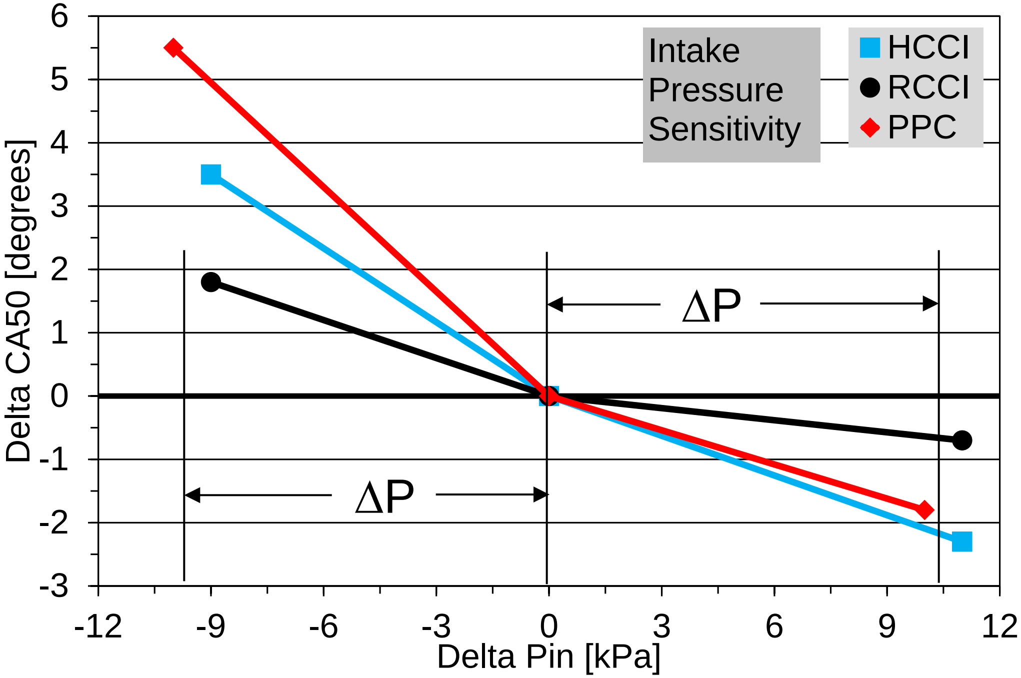


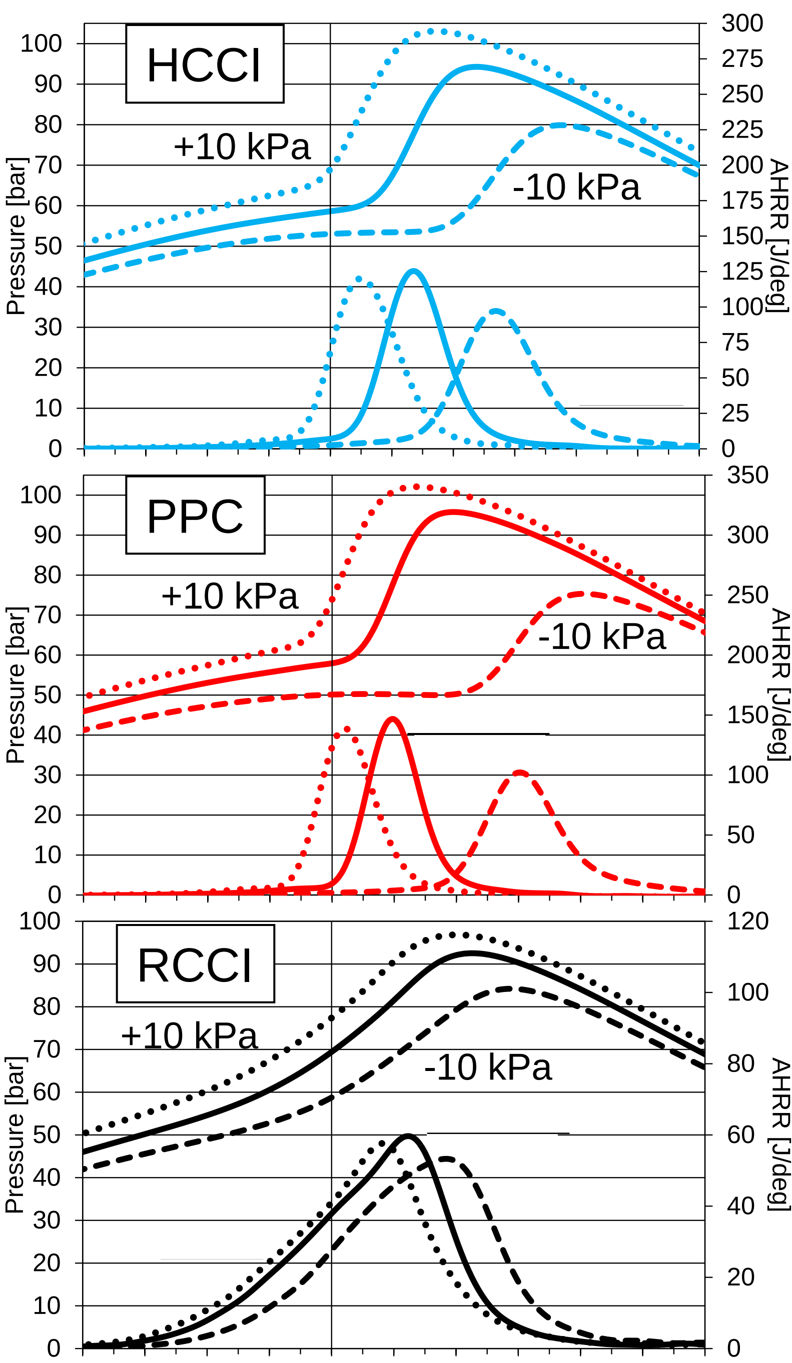


For PPC with PRF94, advancing SOI timing beyond -65˚ ATDC or increasing premixed fuel amount has no impact on combustion phasing

Sensitivity to intake pressure

- Critical for transient operation of turbocharged or supercharged engines.
- Dual-Fuel RCCI is **not** as affected by intake pressure as HCCI or PPC.
- Reasons for these observations are not well understood and will be subject of future simulation research.





Dempsey, 2014

Part 9: Fuels, After-treatment and Controls

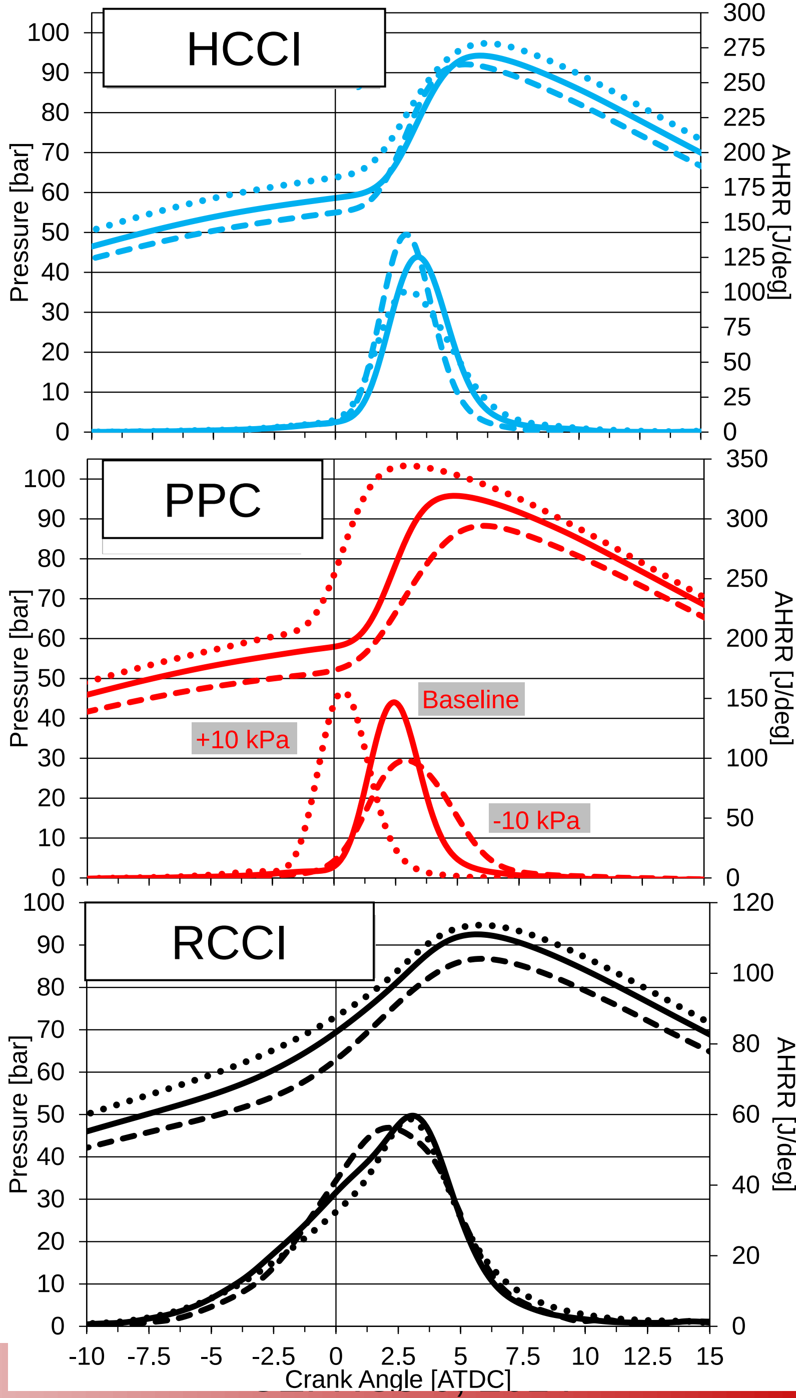
Ability to compensate for ΔP

HCCI	-10 kPa Corrected	Baseline	+10 kPa Corrected
Global PRF #	90.6	93	94.6
CA50 [°ATDC]	3.0	3.5	3.5
NOx [g/kg-fuel]	<0.05	<0.05	<0.05

PPC	-10 kPa Corrected	Baseline	+10 kPa Corrected
Premixed Fuel [%]	65%	79.1%	94.7%
DI Timing [°ATDC]	-35°	-65°	-65°
CA50 [°ATDC]	3.2	2.5	**0.5**
NOx [g/kg-fuel]	**6.8**	<0.05	<0.05

PPC - unable to retard combustion with increased boost

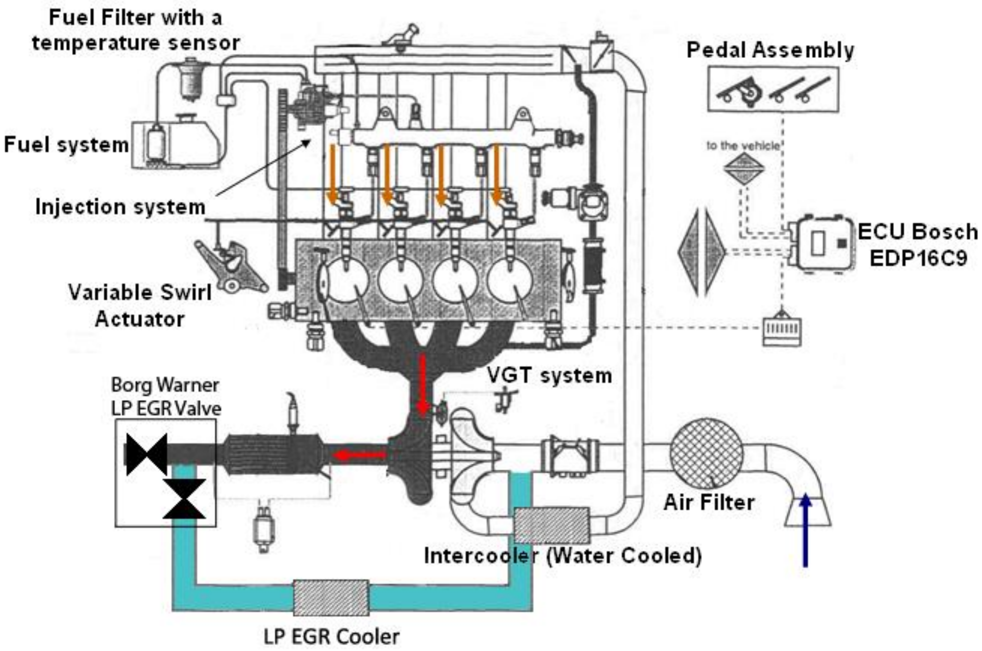
RCCI	-10 kPa Corrected	Baseline	+10 kPa Corrected
Premixed Fuel [%]	91.5%	92.6%	93.5%
DI Timing [°ATDC]	-45°	-45°	-45°
CA50 [°ATDC]	2.2	2.2	2.5
NOx [g/kg-fuel]	<0.05	<0.05	<0.05



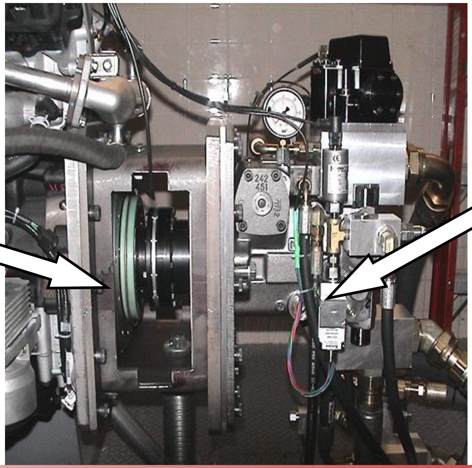
RCCI - transient operation

GM 1.9L Engine Specifications

Engine Type	**EURO IV Diesel**
Bore	82 mm
Stroke	90.4 mm
Displacement	1.9 liters
Cylinder Configuration	Inline 4 4 valves per cylinder
Swirl Ratio	Variable (2.2-5.6)
Compression Ratio	17.5
EGR System	Hybrid High/Low Pressure, Cooled
ECU (OEM)	Bosch EDC16
ECU (new)	Drivven
Common Rail Injectors	Bosch CRIP2-MI 148° Included Angle 7 holes, 440 flow number.
Port Fuel Injectors	Delphi 2.27 g/s steady flow 400 kPa fuel pressure



Hydrostatic dynamometer

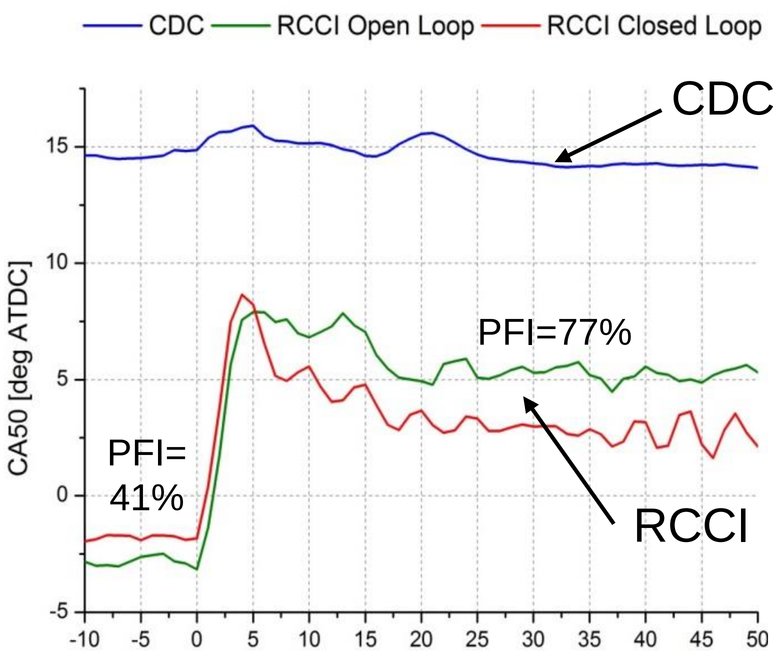


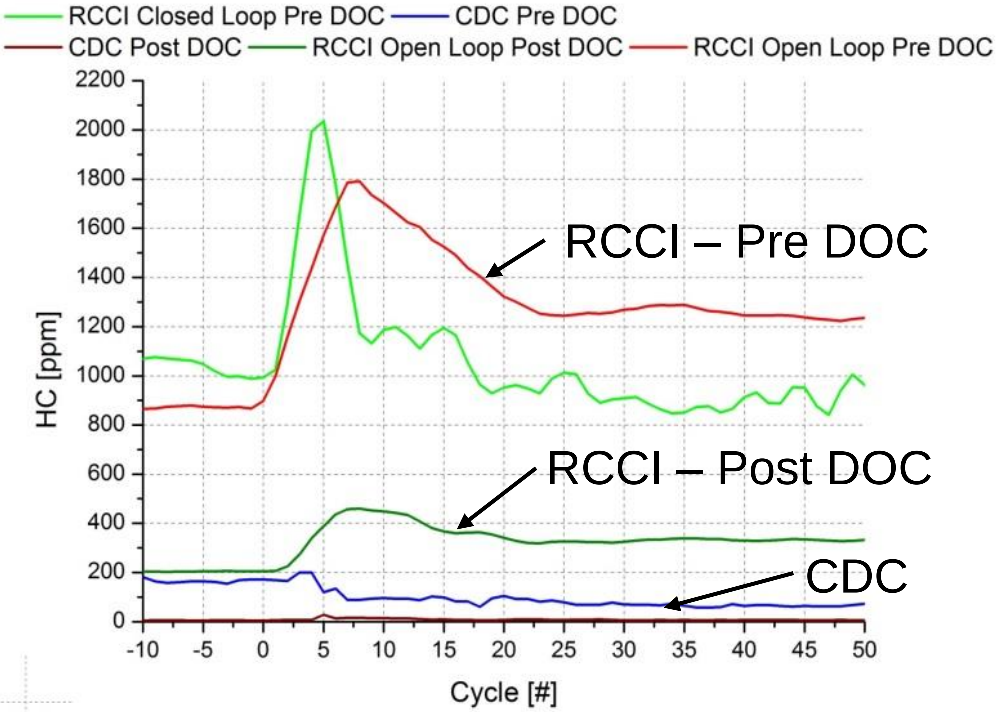
Torque Cell

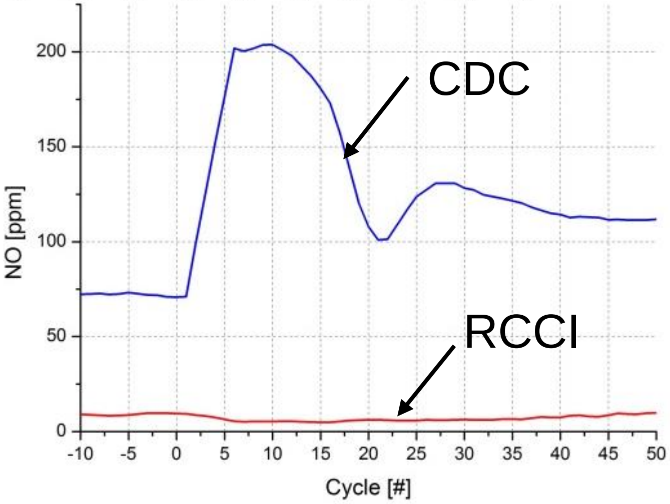
Dyno

Low rotating inertia
-rapid transients (2500 rpm/s)

Step load change: 1 → 4 bar BMEP







RCCI provides considerable transient control since ratio of port to direct-injected fuel can be changed on a cycle-by-cycle basis

Comparison of single fuel LTC, PPC and dual fuel RCCI

Three engines operating with different forms of LTC combustion

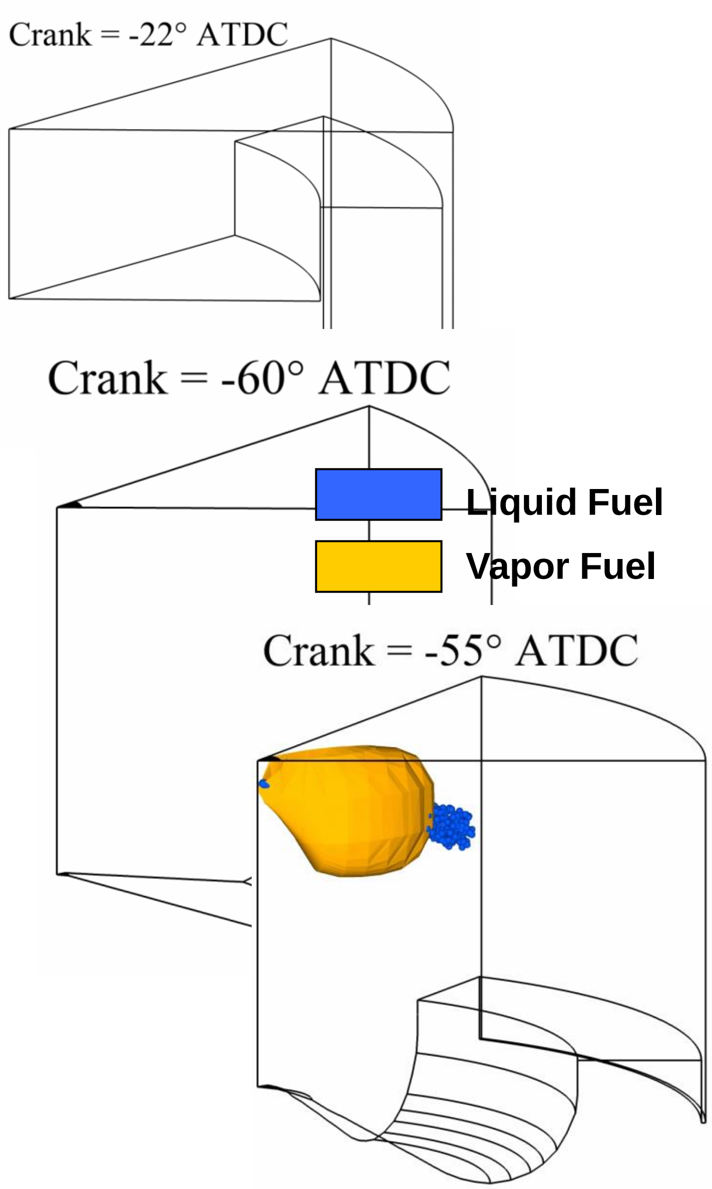
Case	Diesel LTC[1]	Ethanol PPC[2]	Dual-Fuel RCCI[3]
Engine	Cummins N14	Scania D12	CAT 3401
Displacement (cm3)	2340	1966	2440
Stroke (mm)	152.4	154	165.1
Bore (mm)	139.7	127.5	137.2
Con. Rod (mm)	304.8	255	261
CR (-)	11.2	14.3:1	16.1
Swirl Ratio (-)	0.5	2.9	0.7
Number of nozzles	8	8	6
Nozzle hole size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

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

Kokjohn, 2011

Comparison with single fuel LTC

- Diesel LTC
  - Single early injection at 22° BTDC
  - 1600 bar injection pressure
  - Diluted intake (~60% EGR)
- Ethanol PPC
  - 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



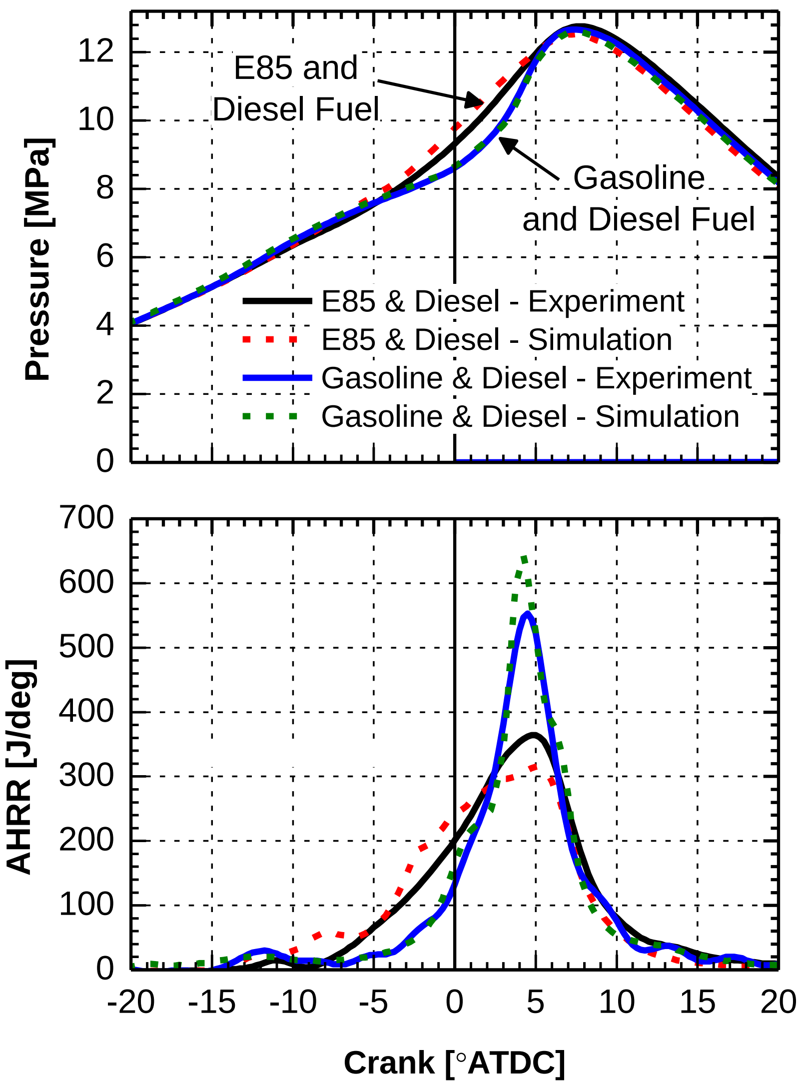
🟦 **Liquid Fuel**

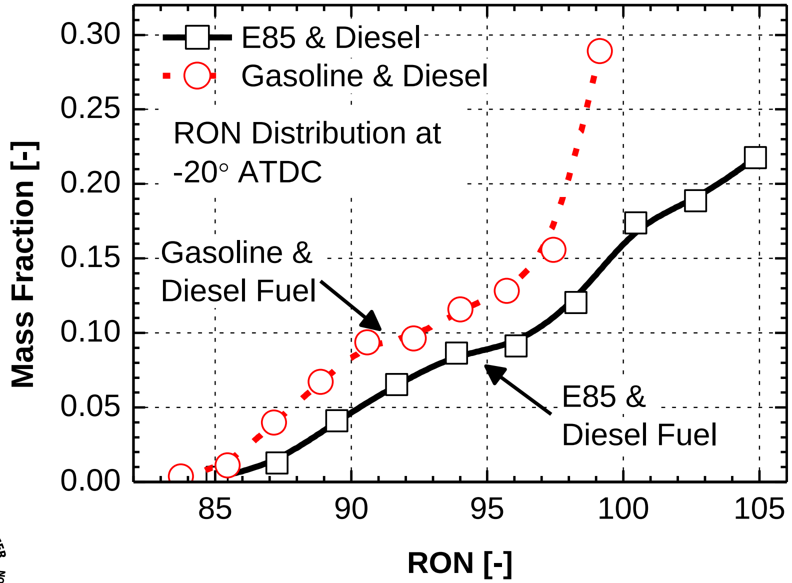
🟨 **Vapor Fuel**

Kokjohn, 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)





Comparison between diesel LTC, ethanol PPC, and RCCI

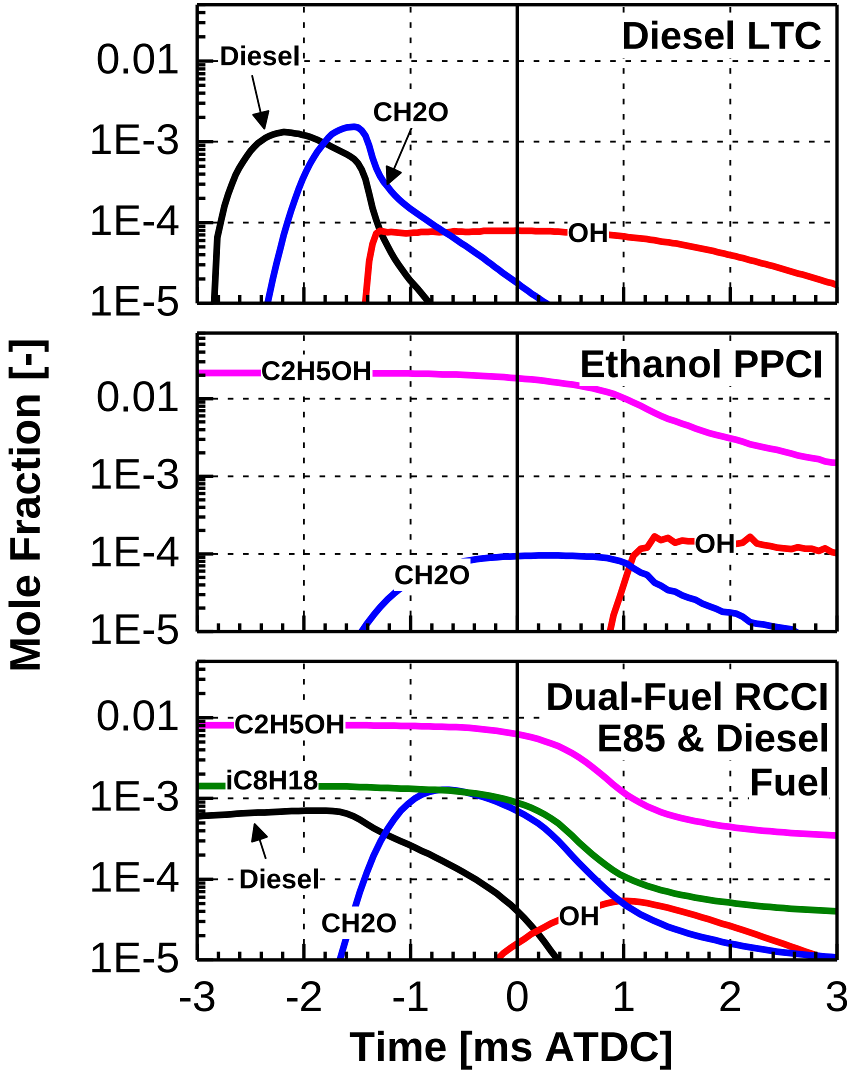
Evolution of key intermediates:

Reaction progress

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

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



Comparison between diesel LTC, ethanol PPC, and RCCI

Diesel LTC

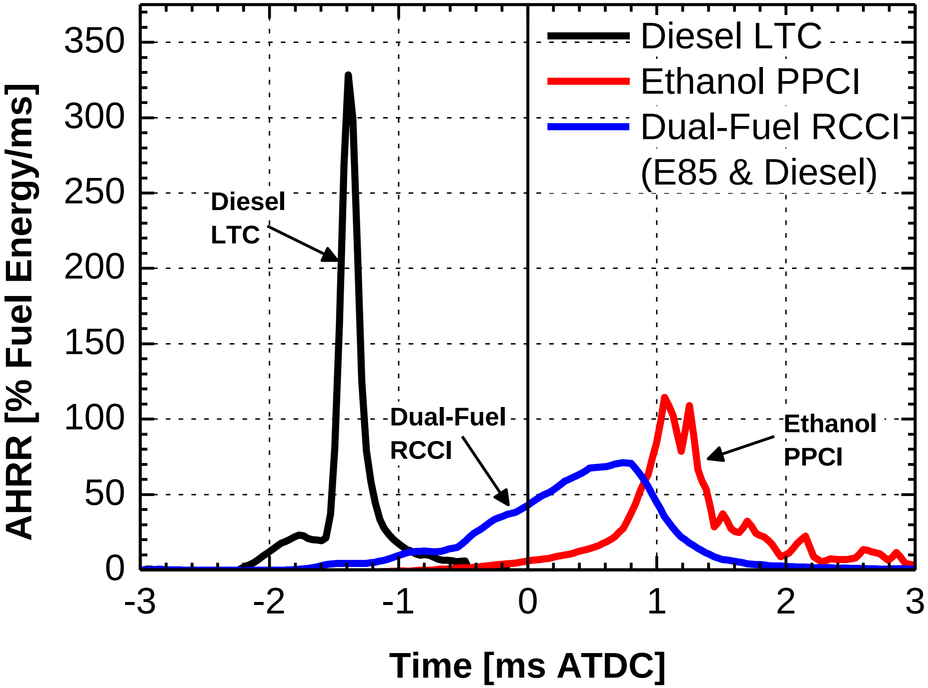
- Earliest combustion phasing and most rapid energy release rate
- High reactivity of diesel fuel requires significant charge dilution to maintain appropriate combustion phasing (12.7% Inlet O_2)

Ethanol PPC

- 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



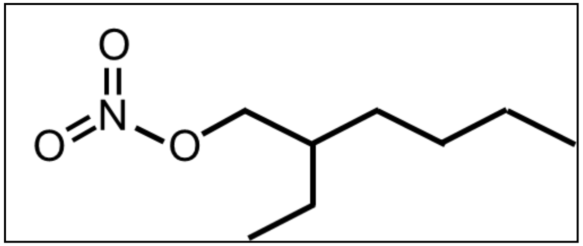
RCCI Engine Experiments
Hanson SAE 2010-01-0864
Kokjohn IJER 2011
Kokjohn SAE 2011-01-0357

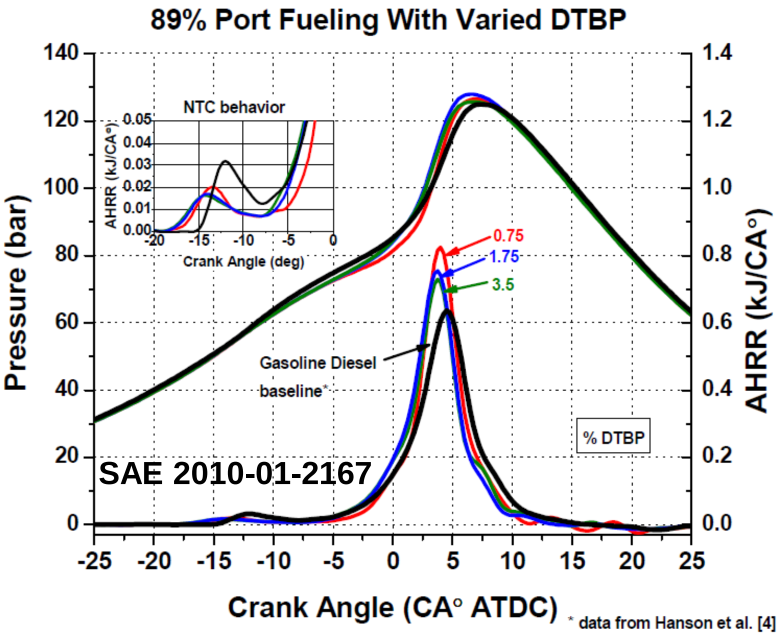
Kaddatz, 2012

‘Single fuel’ RCCI

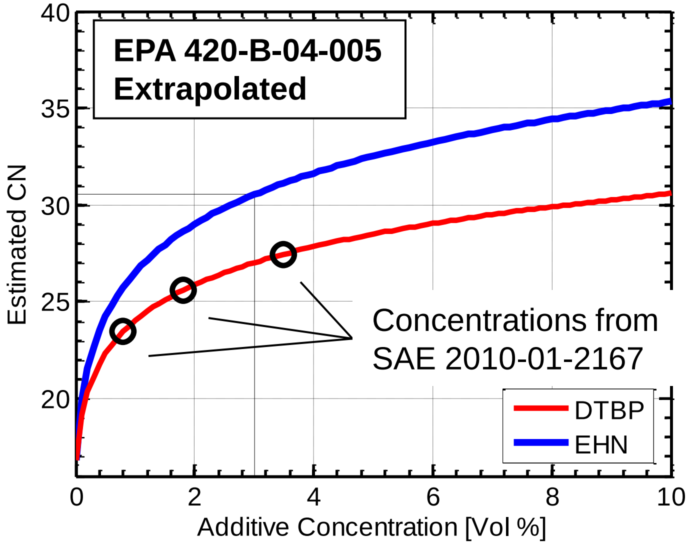
- RCCI is inherently fuel flexible and is promising to control PCI combustion. Can similar results be achieved with a single fuel and an additive?
- Splitter et al. (SAE 2010-01-2167) demonstrated single fuel RCCI in a heavy-duty engine using gasoline + Di-tertiary-Butyl Peroxide (DTBP)
- 2-Ethylhexyl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



Kaddatz, 2012

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)

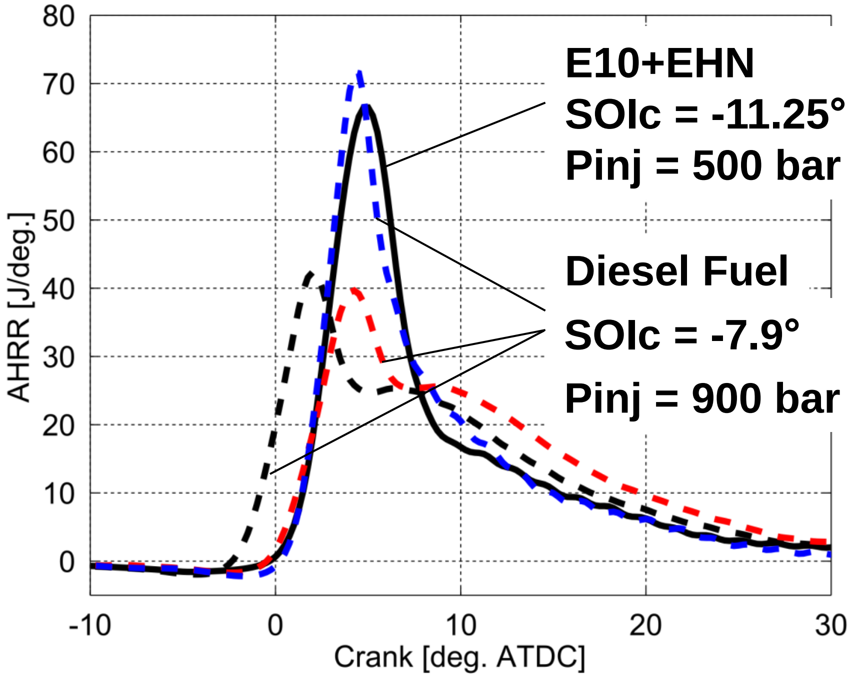
- Diesel fuel injection parameters adjusted to reproduce combustion characteristics of E10+EHN blend

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



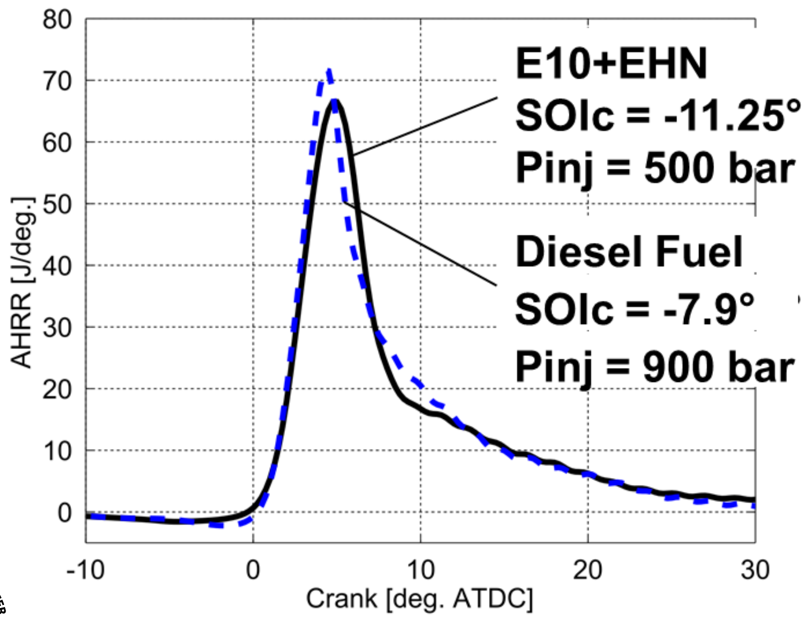
Diesel Fuel

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

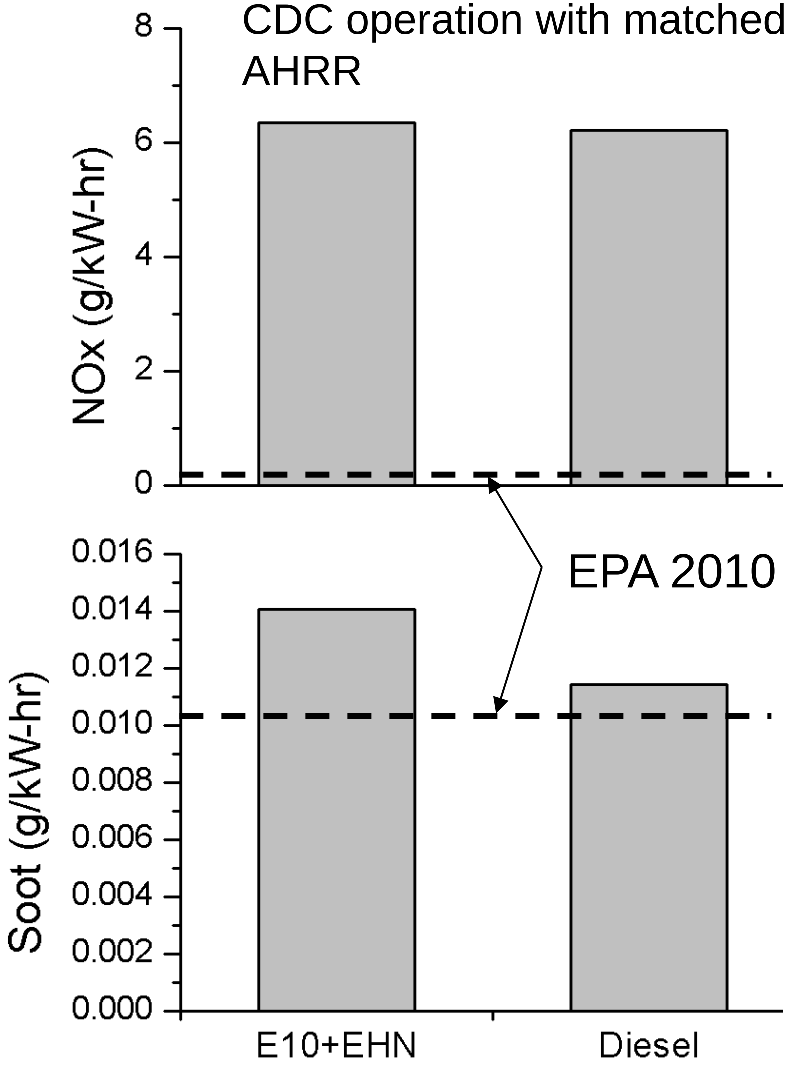
Kaddatz, 2012

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



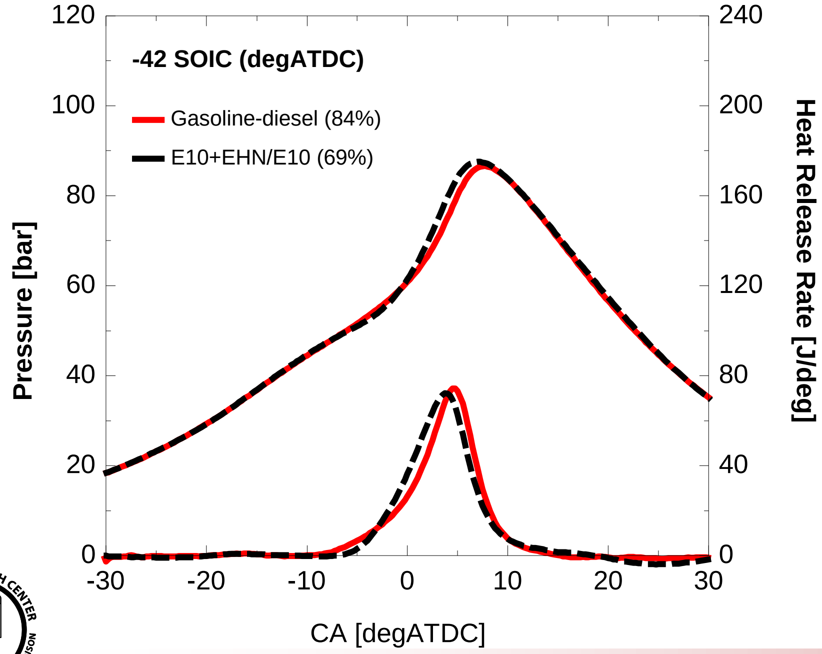
CDC operation with matched AHRR



Kaddatz, 2012

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	

Kaddatz, 2012

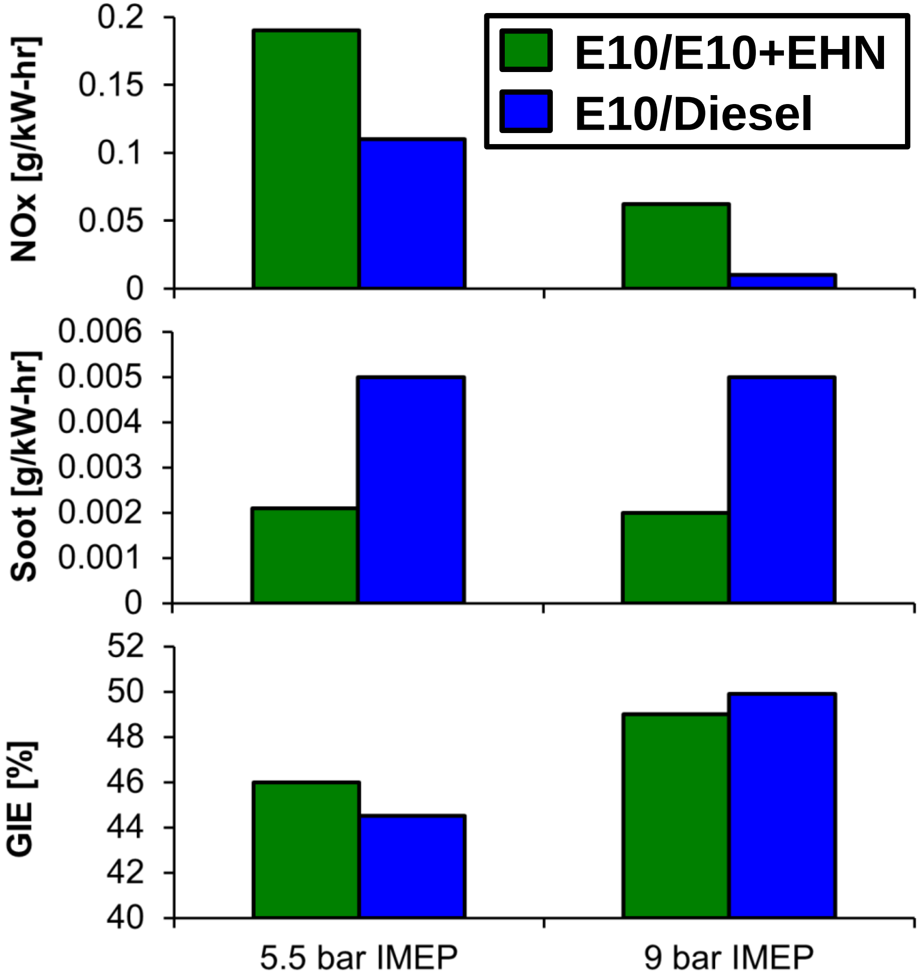
Performance of E10 and E10+EHN RCCI

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

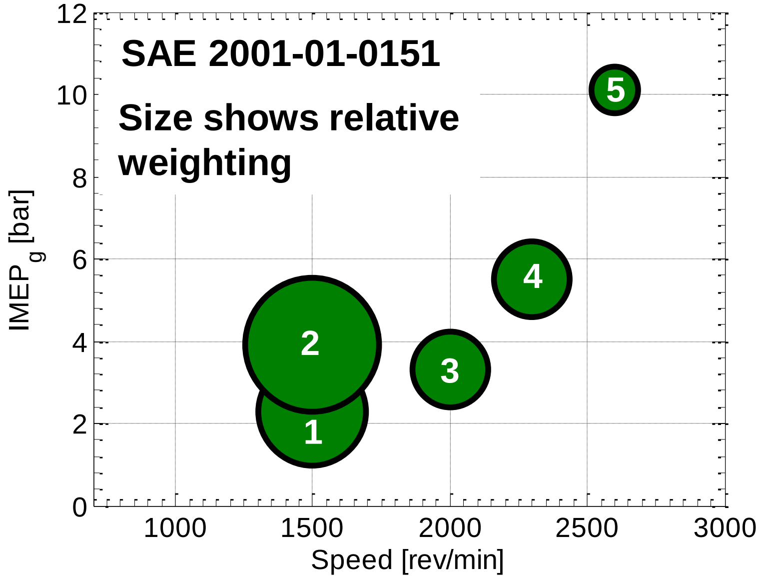
Soot is very low for all cases



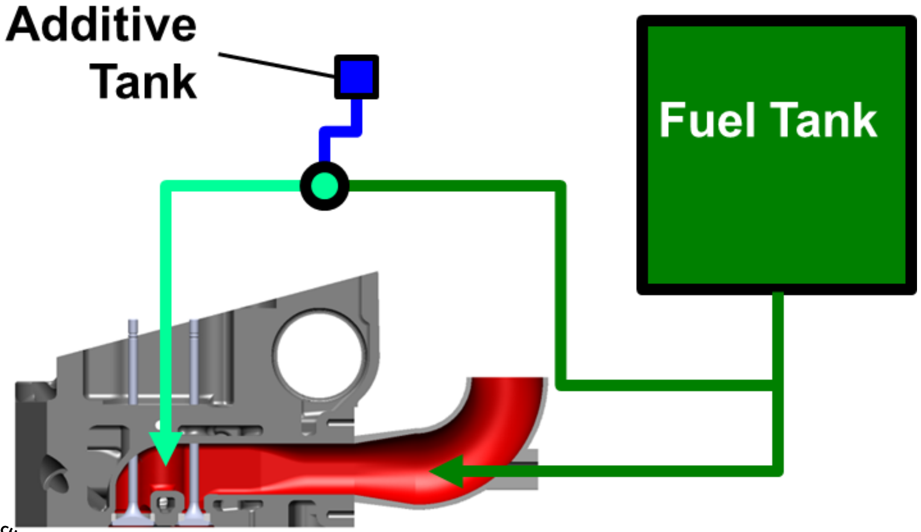
Kaddatz, 2012

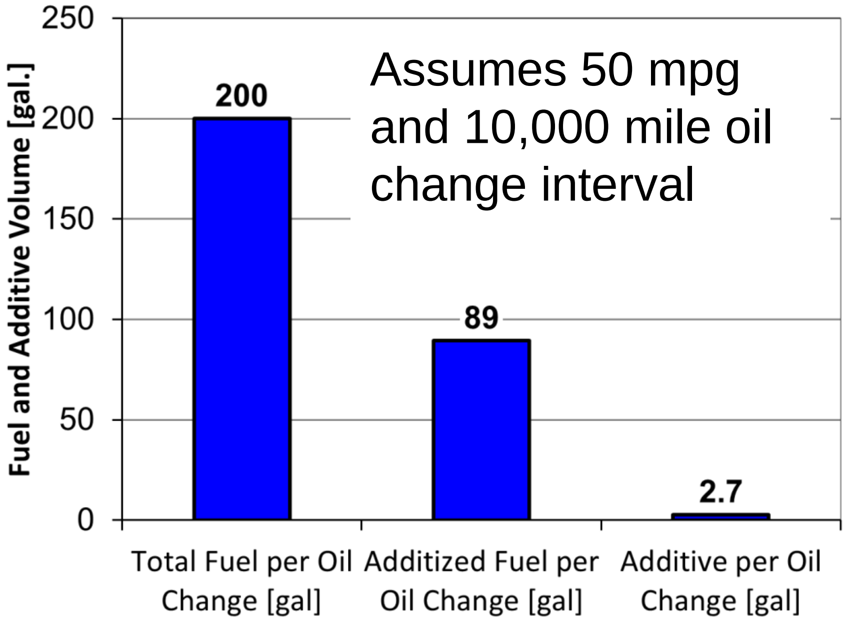
Additive consumption estimate

- 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

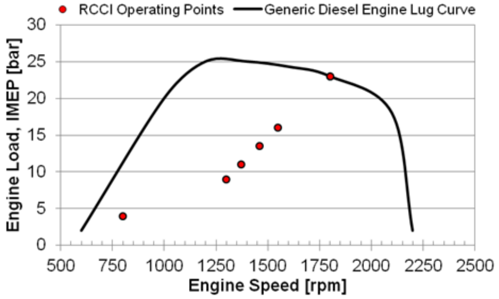



Assumes 50 mpg and 10,000 mile oil change interval

Nieman, 2012

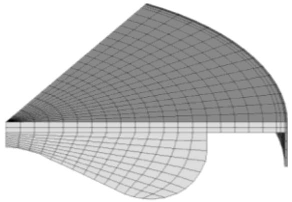
Natural gas/diesel RCCI

Operating Condition	**Low-Load**	**Mid-Load**			**High-Load**	
Gross IMEP [bar]	4	9	11	13.5	16	23
Engine Speed [rpm]	800	1300	1370	1460	1550	1800
Intake Press. [bar abs.]	1.00	1.45	1.94	2.16	2.37	3.00
Intake Temp. [°C]	60	60	60	60	60	60



ERC KIVA PRF kinetics
NSGA-II MOGA
32 Citizens per Generation
~9500 Cells @ BDC
UW Condor - Convergence after ~40 generations

Caterpillar 3401E SCOTE	
Displacement [L]	2.44
Bore x Stroke [mm]	137.2 x 165.1
Con. Rod Length [mm]	261.6
Compression Ratio	16.1:1
Swirl Ratio	0.7
IVC [deg ATDC]	-143
EVO [deg ATDC]	130
Common Rail Diesel Fuel Injector	
Number of Holes	6
Hole Diameter [μm]	250
Included Spray Angle	145°



Design Parameter	**Minimum**	**Maximum**
Premixed Methane [%]	0%	100%
DI Diesel SOI 1 [deg ATDC]	-100	-50
DI Diesel SOI 2 [deg ATDC]	-40	20
Diesel Fraction in First Inj. [%]	0%	100%
Diesel Injection Pressure [bar]	300	1500
EGR [%]	0%	60%

Nieman, 2012

GA optimized NOx, Soot, CO, UHC ISFC, PPRR

Design Parameter	**4 bar**	**9 bar**	**11 bar**	**13.5 bar**	**16 bar**	**23 bar**
Engine Speed [rpm]	800	1300	1370	1460	1550	1800
Total Fuel Mass [mg]	40	89	109	133	158	228
Methane [%]	73%	85%	87%	90%	87%	85%
Diesel SOI 1 [deg ATDC]	-52.9	-87.3	-87.2	-79.5	-81.1	-92.7
Diesel SOI 2 [deg ATDC]	-22.5	-38.3	-39.4	-39.6	-39.7	-20.4
Diesel in 1st Inj. [%]	52%	40%	39%	55%	49%	70%
Diesel Inj. Press. [bar]	1300	954	465	822	594	742
EGR [%]	5%	0%	0%	0%	32%	48%

- Clean, efficient operation up to 13.5 bar IMEP without needing EGR

Results

* -180° to 180° ATDC

Results						
Soot [g/ikW-hr]	0.004	0.002	0.002	0.002	0.003	0.079
NOx [g/ikW-hr]	0.24	0.25	0.08	0.07	0.15	0.08
CO [g/ikW-hr]	10.8	0.2	0.9	0.8	0.5	6.0
UHC [g/ikW-hr]	10.5	0.5	2.2	2.4	1.5	9.4
η_{gross} [%] *	45.1%	50.4%	50.6%	48.9%	49.2%	44.1%
PPRR [bar/deg]	2.7	5.1	8.1	4.4	5.7	5.0
Ring. Intens. [MW/m^2]	0.2	1.5	2.8	1.0	1.8	1.5

Meet EPA 2010 (except soot at high load)

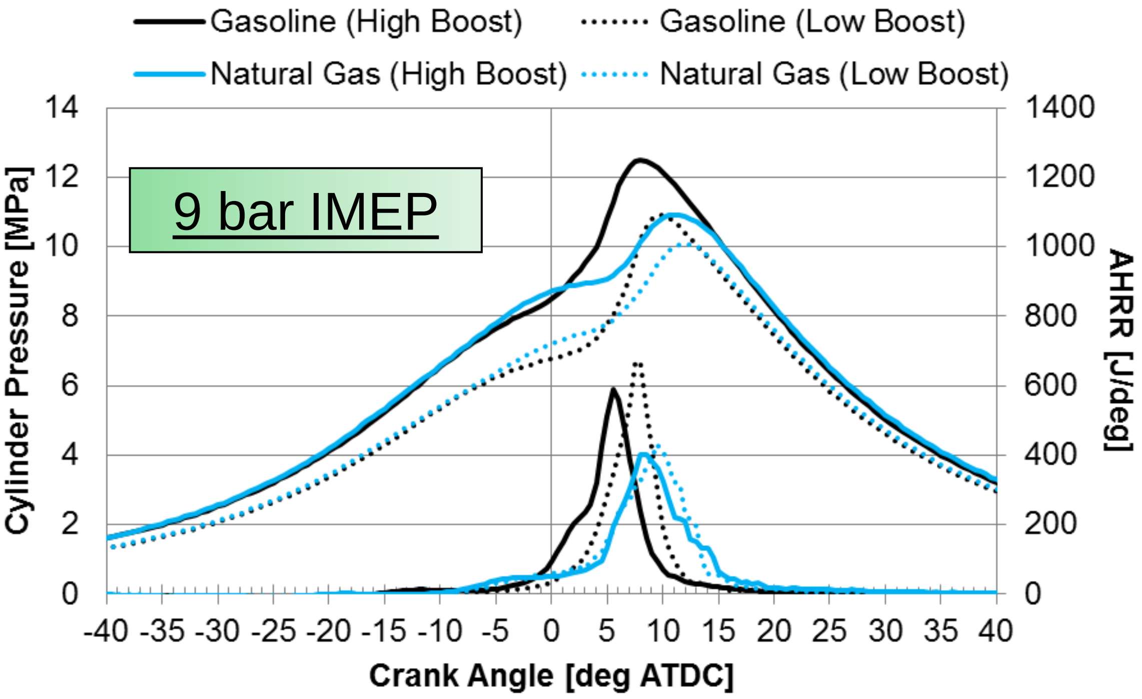
High peak thermal efficiency

- Low PPRR

Extend range to lower/high loads with triple injections

Nieman, 2012

Comparison with gasoline/diesel RCCI



Gasoline/Diesel strategy optimized at 1.75 bar abs. (high boost)

Natural Gas/Diesel used 1.45 bar abs. (low boost)

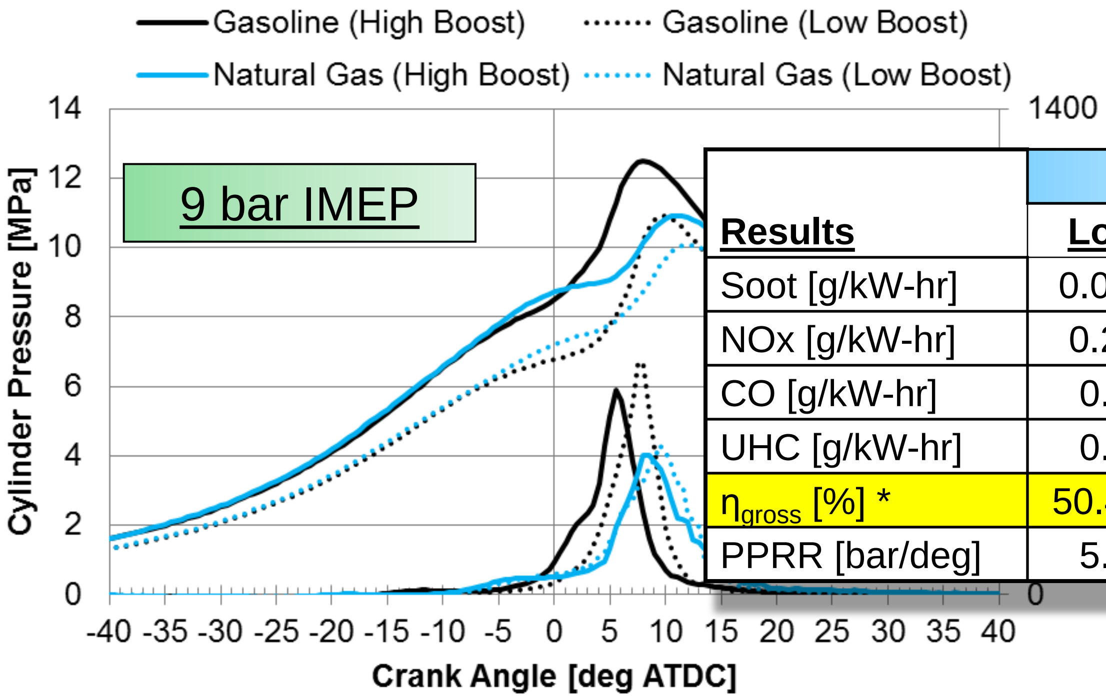
Each run at both conditions

Quite similar strategies

Design Parameter	**Nat. Gas/ Diesel**	**Gasoline/ Diesel**
Intake Temperature [°C]	60	32
Total Fuel Mass [mg]	89	94
Low-Reactivity Fuel (Premixed) [%]	85%	89%
Diesel SOI 1 [deg ATDC]	-87.3	-58.0
Diesel SOI 2 [deg ATDC]	-38.3	-37.0
Diesel in 1st Inj. [%]	40%	60%
EGR [%]	0%	43%

Nieman, 2012

Comparison with gasoline/diesel RCCI



	Nat. Gas		**Gasoline**	
Results	**Low**	**High**	**Low**	**High**
Soot [g/kW-hr]	0.002	0.003	0.007	0.014
NOx [g/kW-hr]	0.25	0.02	0.02	0.01
CO [g/kW-hr]	0.2	1.8	1.2	3.6
UHC [g/kW-hr]	0.5	2.5	2.7	4.0
η_{gross} [%] *	50.4%	50.4%	52.1%	52.2%
PPRR [bar/deg]	5.1	4.8	10.6	9.9

* -180° to 180° ATDC

Design Parameter	**Nat. Gas/ Diesel**	**Gasoline/ Diesel**
Intake Temperature [°C]	60	32
Total Fuel Mass [mg]	89	94
Low-Reactivity Fuel (Premixed) [%]	85%	89%
Diesel SOI 1 [deg ATDC]	-87.3	-58.0
Diesel SOI 2 [deg ATDC]	-38.3	-37.0
Diesel in 1st Inj. [%]	40%	60%
EGR [%]	0%	43%

- *2% Efficiency Difference:*

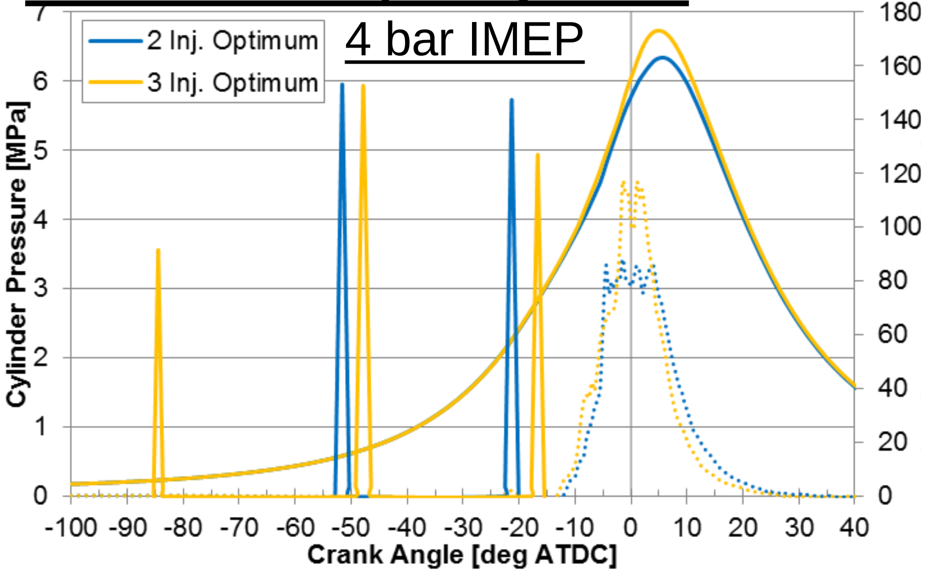
Higher in-cyl. temps and comb. in squish

↓

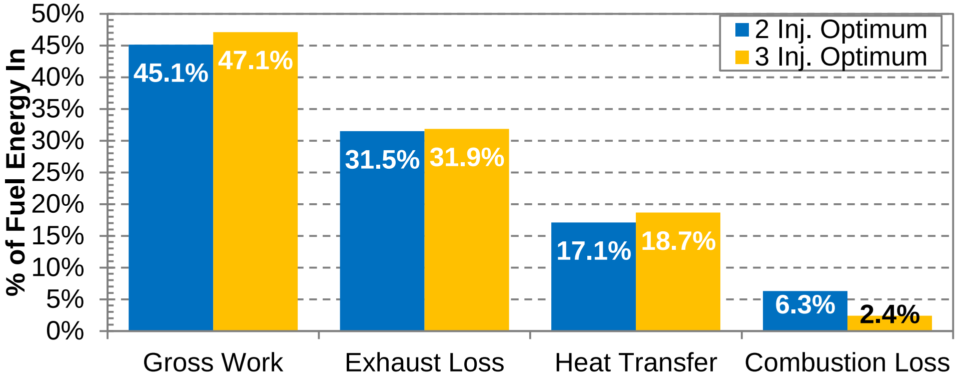
Greater HT Losses

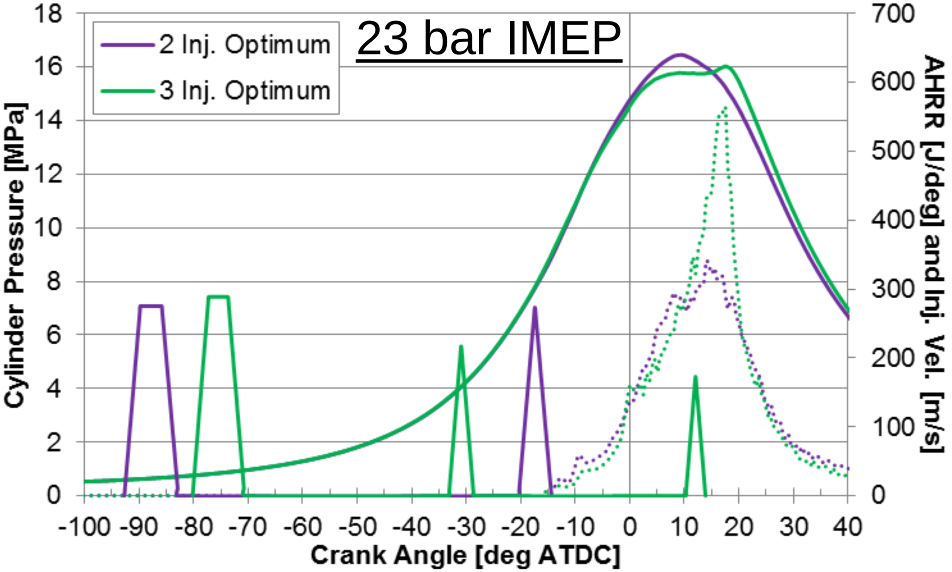
Nieman, 2012

Double vs. Triple Injection

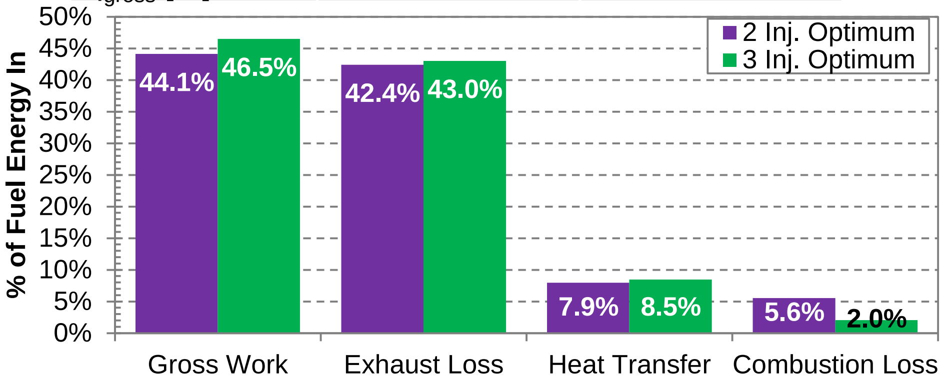


Results	2 Inj. Optimum	3 Inj. Optimum
Soot [g/kW-hr]	0.004	0.004
NOx [g/kW-hr]	0.24	0.10
CO [g/kW-hr]	10.8	7.3
UHC [g/kW-hr]	10.5	3.8
η_{gross} [%]	45.1%	47.1%



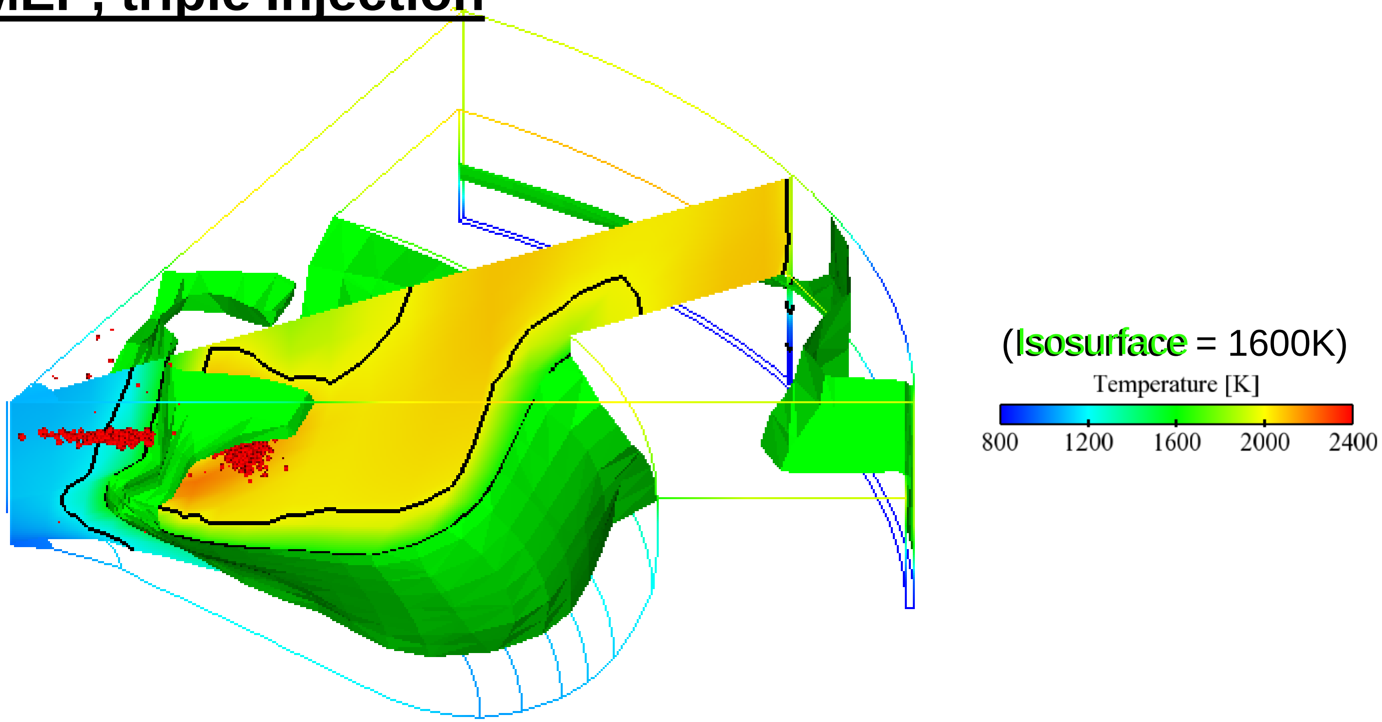


Results	2 Inj. Optimum	3 Inj. Optimum
Soot [g/kW-hr]	0.079	0.014
NOx [g/kW-hr]	0.08	0.17
CO [g/kW-hr]	6.0	1.7
UHC [g/kW-hr]	9.4	3.3
η_{gross} [%]	44.1%	46.5%



Nieman, 2012

23 bar IMEP, triple Injection



18° ATDC

- Can achieve low soot, despite late 3rd injection
  - Combustion starts in squish region, so diesel #3 injects into a relatively cool environment
  - Fairly small amount injected

Nieman, 2012

Natural gas composition effects

- Optimization studies assumed nat. gas = pure methane
- Ethane can also be in substantial concentration
- 23 bar IMEP triple injection strategy
  - Replace some metha

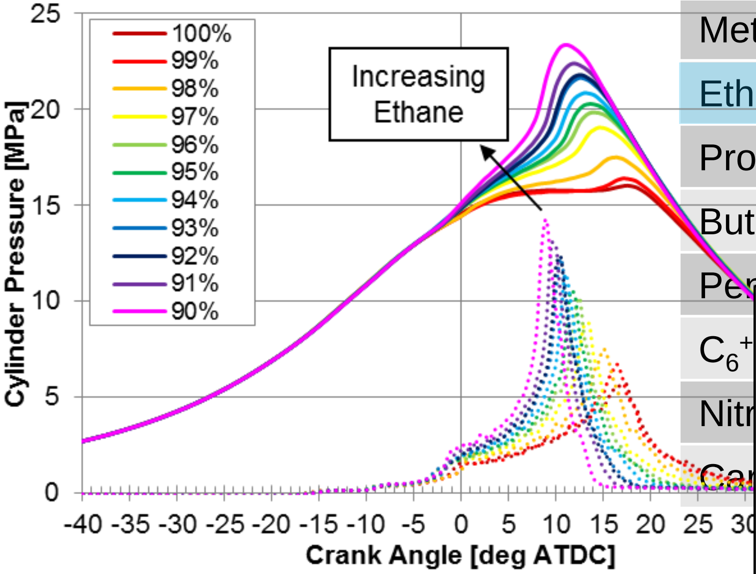
Species Name	Content
Methane	92%
Ethane	3%
Propane	0.7%
Butane	0.02%
Pentane	0.1%
C_6^+	
Nitr	
Car	

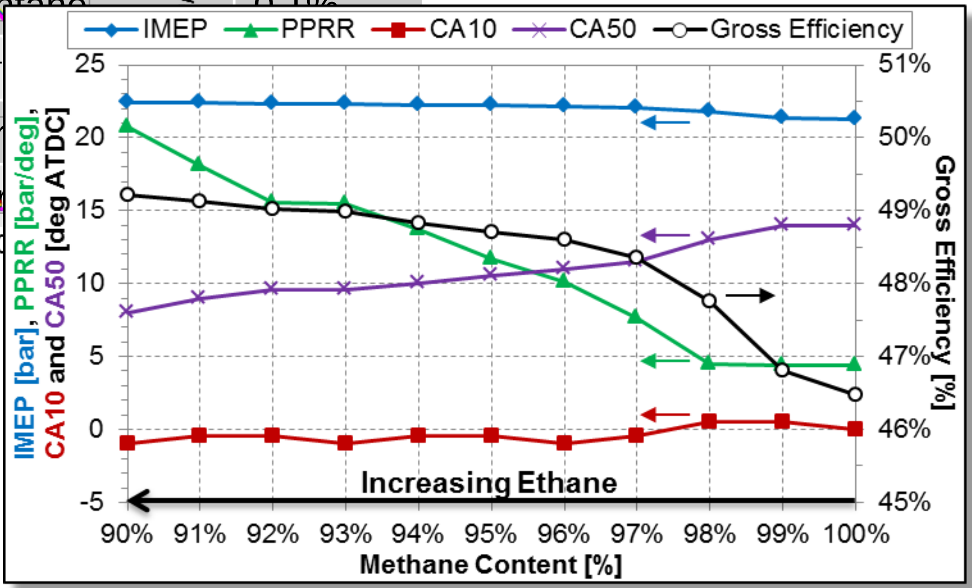
ane enhances combustion

ncreases reactivity of premix

hortens combustion duration

ncreases combustion efficiency





Nieman, 2012

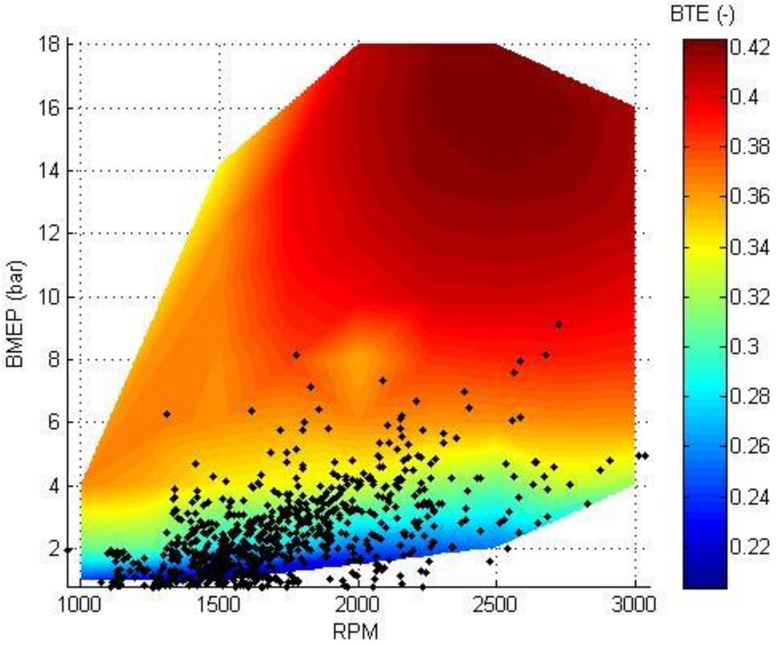
NG/diesel RCCI summary

- Use of natural gas as the low-reactivity fuel in conjunction with diesel fuel in RCCI combustion investigated.
- Modeling of NG/diesel RCCI showed good combustion phasing could be achieved over a wide range of intake temperatures. Changes in intake T can be accounted for by varying NG/diesel ratio.
- MOGA has been used to develop strategies for RCCI operation from low-load/low-speed to high-load/high-speed.
  - US 2010 HD regulations met, in-cylinder (require 3 injections at high load)
  - High NOx/soot & low(er) comb. eff. observed in low- and high-loads
  - Operation controlled by NG/diesel ratio and injection schedule
- MOGA studies show that utilizing triple injections extends the low- and high-load operating ranges
  - Added flexibility = decreased NOx/soot, increased combustion efficiency
- Study of nat. gas composition effects shows that ethane/propane/etc. concentrations have substantial effect on reactivity of NG (i.e., comb. phasing, duration, and completeness).
  - Small amounts (1-3%) enhanced combustion

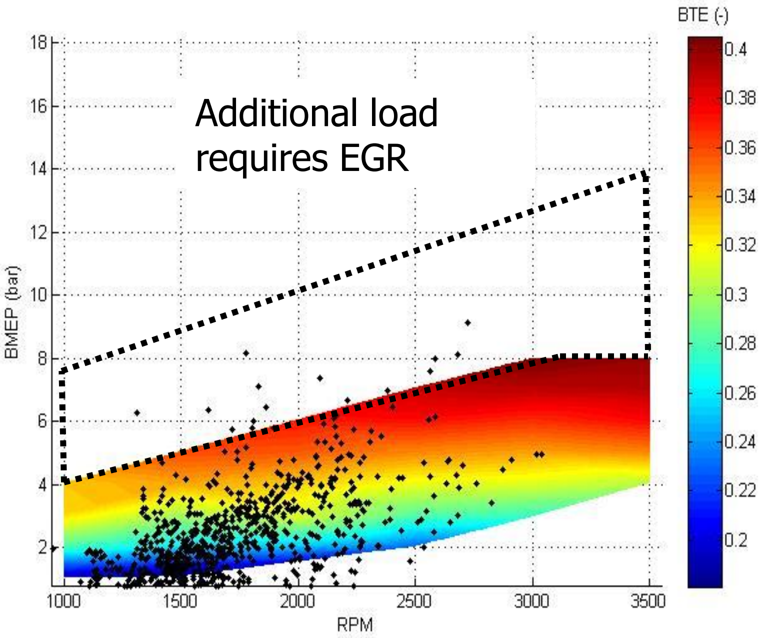
Prikhodko, 2010

RCCI after-treatment requirements

CDC



RCCI



Additional load requires EGR

Experiments in collaboration with Oak Ridge National Laboratory

RCCI operating range covers most of EPA FTP drive area

Cooled and/or LP EGR can be used to extend max load with RCCI

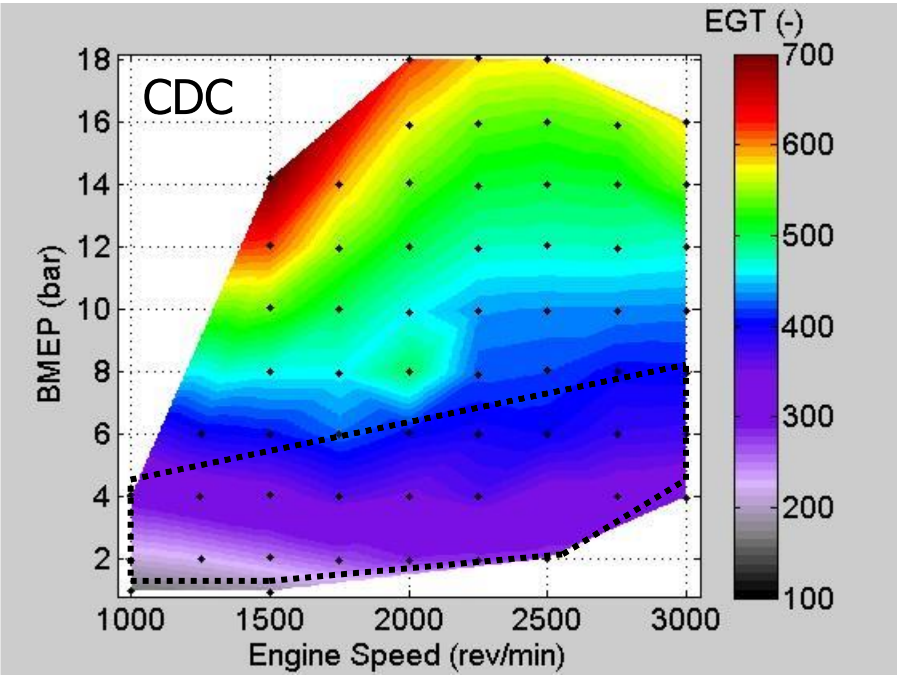
- UW H-D engine typically gains 50-100% more load with EGR

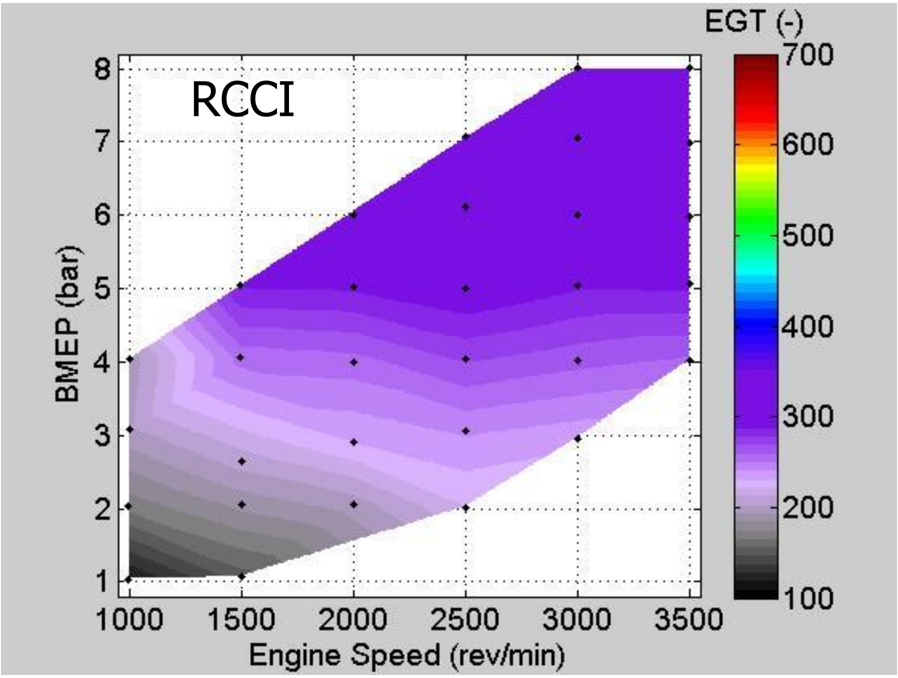
(CDC - 2007 Opel Astra 1.9L, data from ANL)

Prikhodko, 2010

Exhaust temperature

- RCCI shows 50-100 °C lower turbine inlet temperature than CDC
- Reduced exhaust availability for turbocharging and after-treatment systems
- Low load operation with RCCI is a challenge with the OEM turbocharger
  - Lower temperatures drop exhaust enthalpy, increasing pumping work and limiting thermal efficiency
  - Improved turbo-machinery exists for this engine, which could improve the performance
- Low EGTs in the FTP driving area are a challenge for oxidation catalyst performance
  - Need 90+% catalyst efficiency to meet HC and CO targets, challenging with EGTs ~ 200 ° C

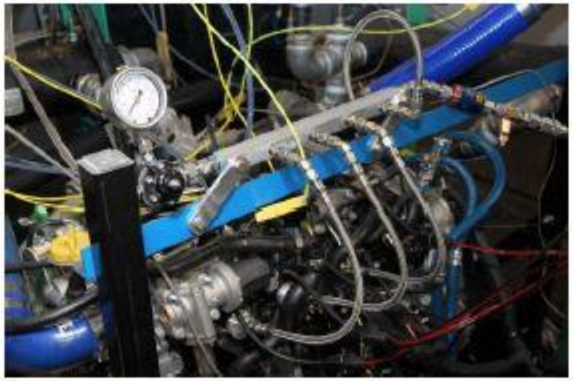




Prikhodko, 2010

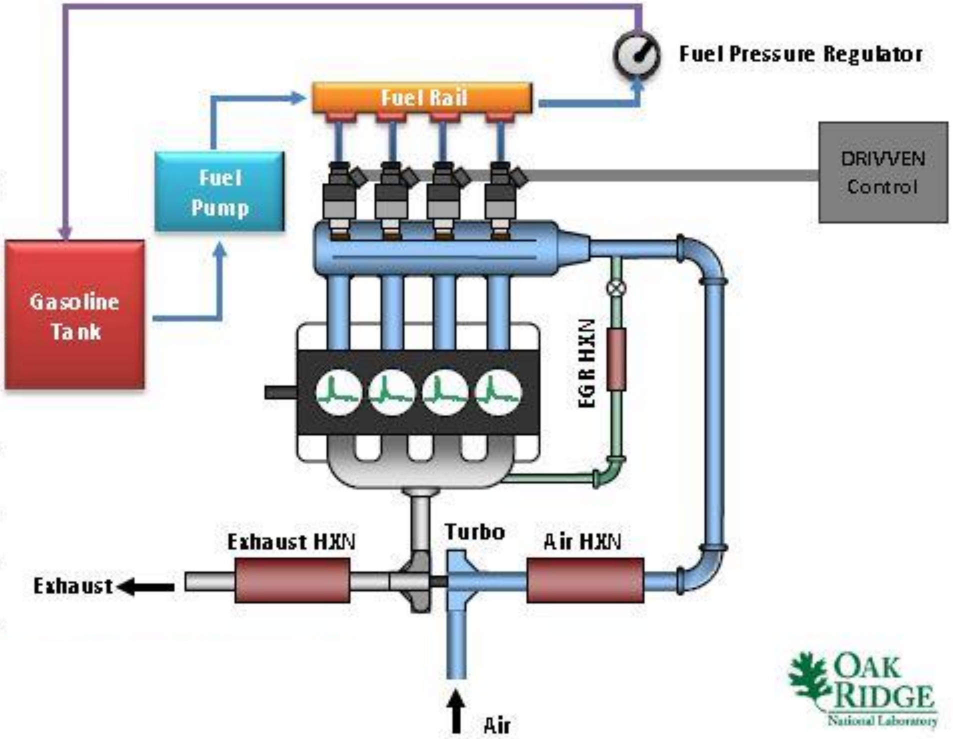
ORNL RCCI experiments

- SAE 2010 RCCI ("dual-fuel") approach from Univ. of Wisconsin (UW) demonstrated on ORNL multi-cylinder engine
  - +1.5% efficiency (η_T) and low NOx demonstrated
- ORNL collaborating with UW to compare UW model to ORNL multi-cylinder experimental results



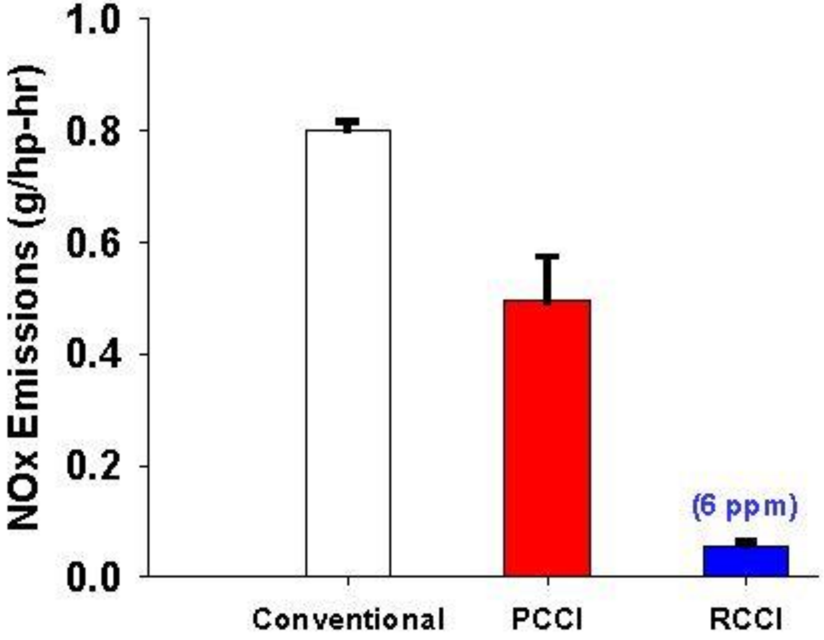
2300 rpm, 4.2 bar BMEP condition (no EGR)

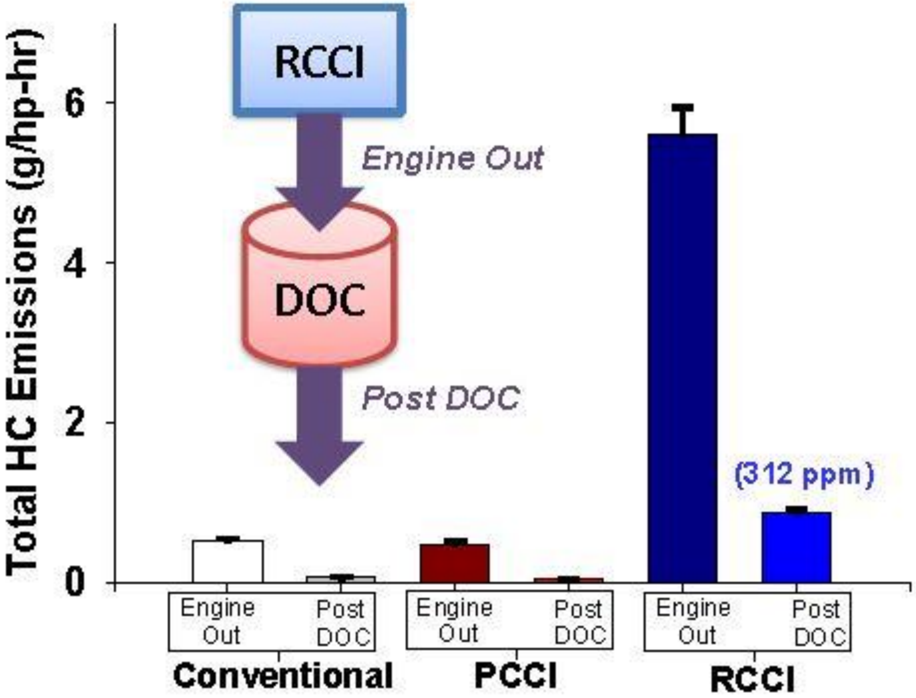
	Conventional Diesel	RCCI (77% Gasoline)
BTE (%)	32.1	33.6
NOx (ppm)	94	7.5
FSN	1.78	0.02
CO (ppm)	423	1512
HC (ppm)	296	2581
Exhaust T (C)	412	260



Prikhodko, 2010

CDC, PCCI & RCCI NOx and HC emissions





- RCCI PM has high organic content and small size indicative of hydrocarbon-heavy aerosols
- DOC found to be effective in reducing PM emissions and hydrocarbon emissions from RCCI
- Resulting RCCI tailpipe emissions are very low for NOx without NOx catalyst

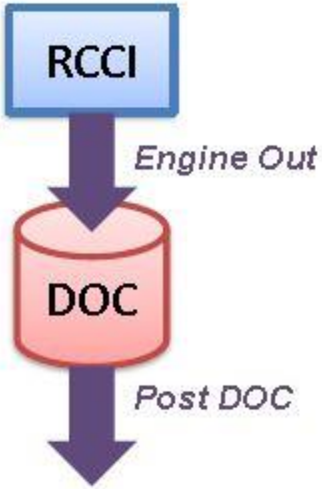
RCCI is fuel-efficient with emissions that can largely be controlled with DOC alone thus reducing the fuel penalty and cost of the aftertreatment system

Managed by UT-Battelle
for the U.S. Department of Energy

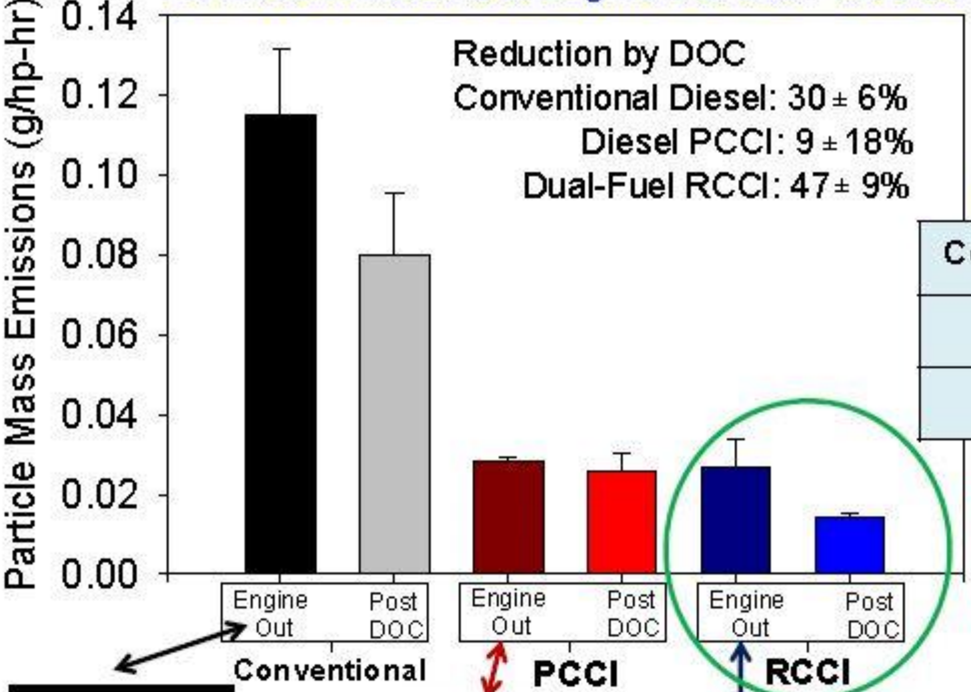
Prikhodko, 2010

CDC, PCCI & RCCI PM emissions

- RCCI particulate matter (PM) found to be very different from conventional and PCCI PM
- PM filter images and size distribution data suggested high organic content in PM from RCCI
- DOC reduces RCCI PM mass significantly



PM mass emissions at Engine Out and Post DOC



Exhaust Temperature

Conventional	415°C
PCCI	420°C
RCCI	250°C

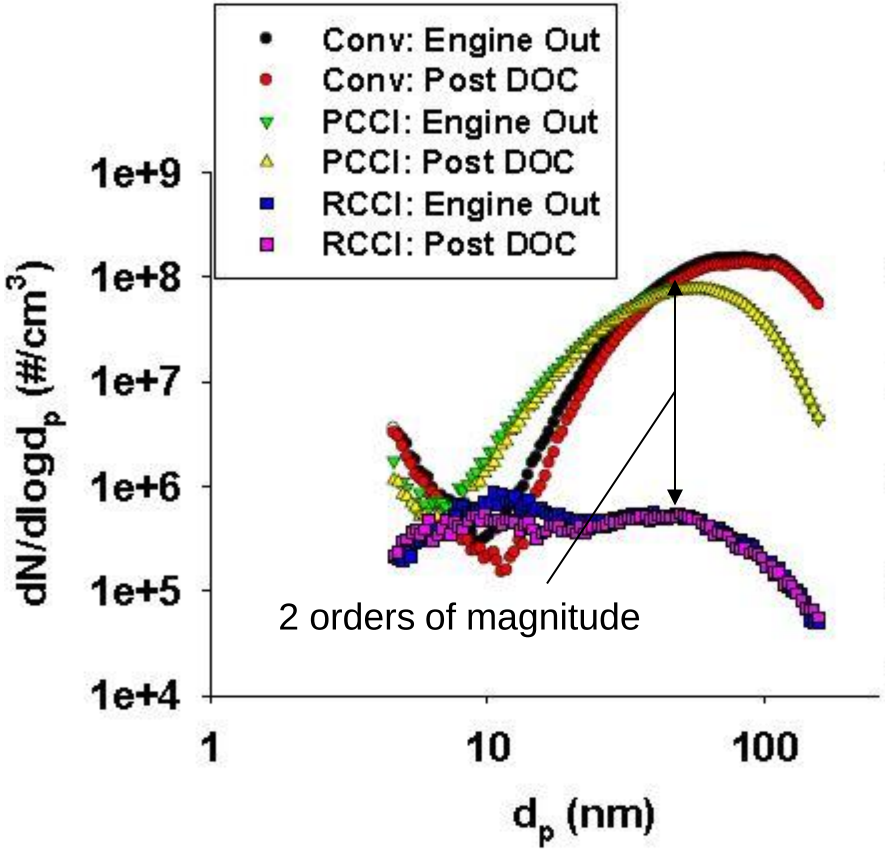
DOC effective for RCCI PM even though exhaust temperature lower

PM filter samples at Engine Out

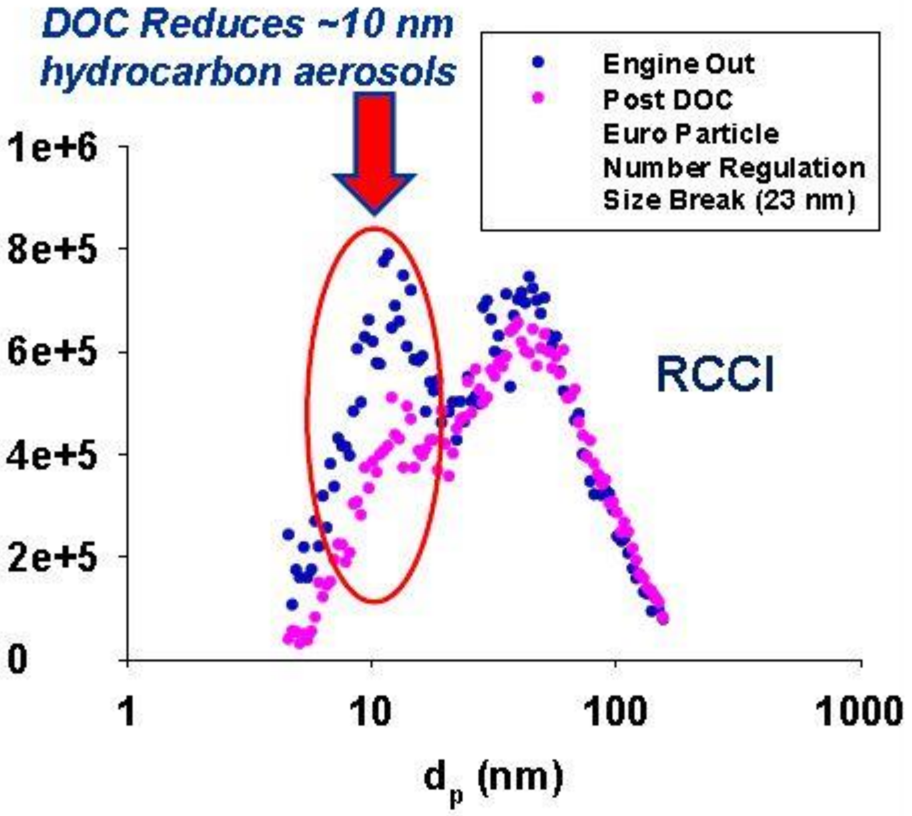
Prikhodko, 2010

RCCI - low particle number

- **Scanning Mobility Particle Sizer (SMPS) shows PM size distribution differs for conventional, PCCI, and RCCI particulate**
- **RCCI PM has bimodal distribution**
- **DOC effective at reducing RCCI PM in ~10 nm range but not ~60 nm range**



2 orders of magnitude


DOC Reduces ~10 nm hydrocarbon aerosols

Note: log y-axis for plot on left <u>but</u> linear y-axis for plot on right

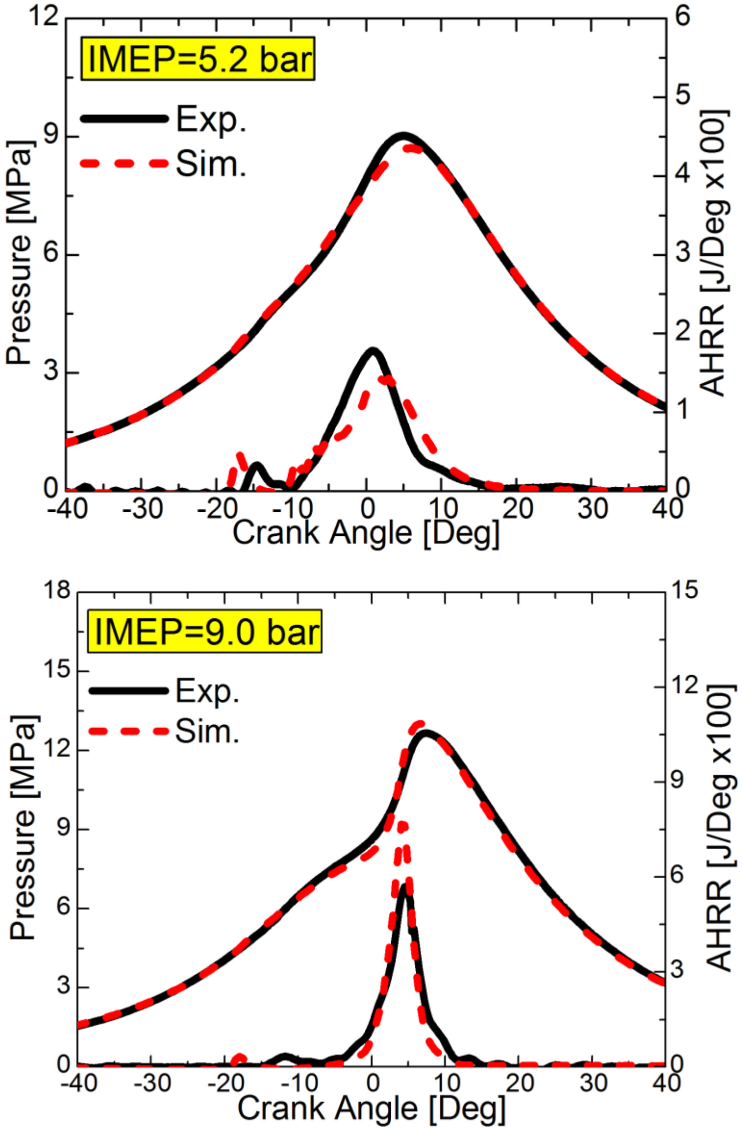
Qiu, 2014

<u>Modeling organic fraction</u> - Condensed fuel

Caterpillar SCOTE – 1300 rev/min

Gross IMEP (bar)	5.2	9.0
Premixed Gasoline (Mass %)	68%	89%
Diesel SOI1 (°ATDC)	-58	
Diesel DOI1 (°CA)	5.07	3.9
Diesel SOI2 (°ATDC)	-37	
Diesel DOI2 (°CA)	2.34	1.95
Diesel in Injection #1 (Mass %)	62%	64%
Intake Tank Temperature (°C)	32	
EVO Timing (°ATDC)	130	
IVC Timing (°ATDC)	-143	
Intake Pressure (bar)	1.38	1.75
Exhaust Pressure (bar)	1.45	1.84
EGR Rate (%)	0	43

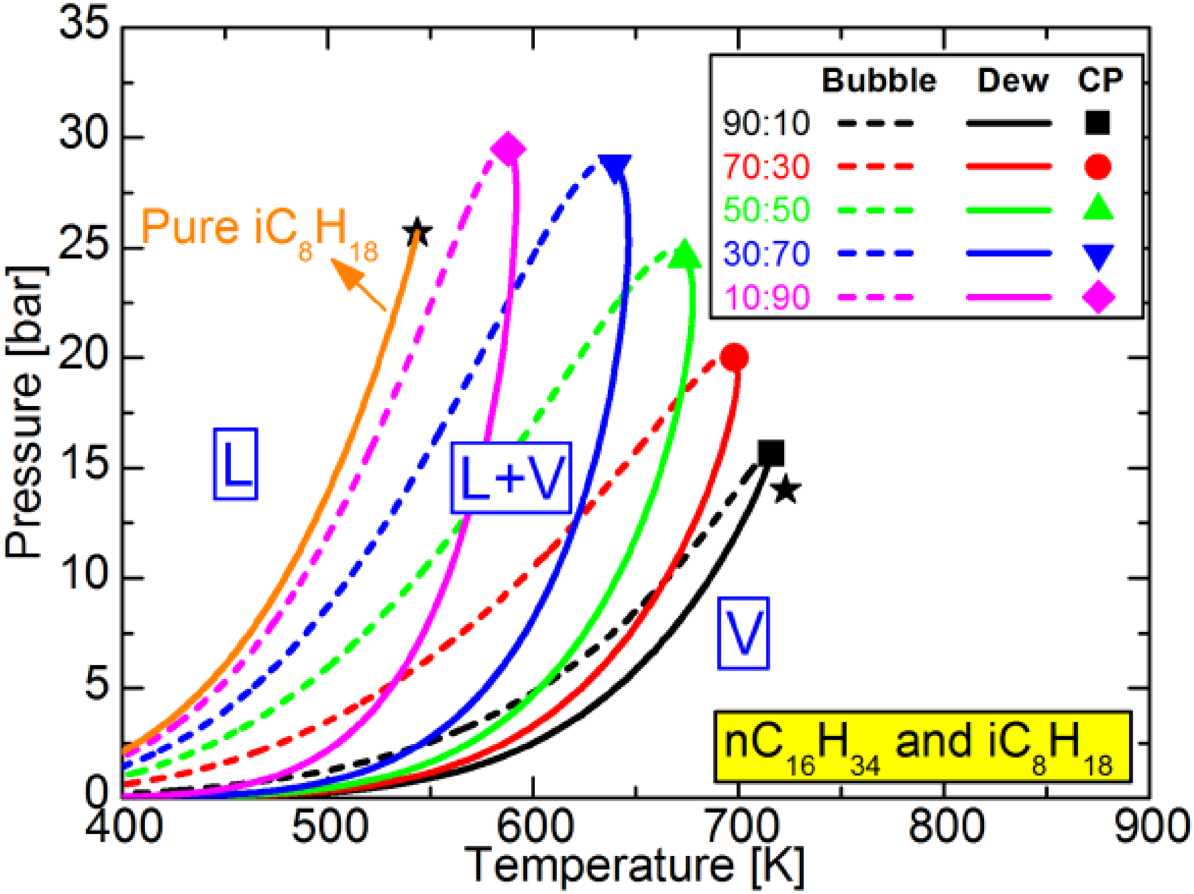
Premixed iso-octane as gasoline surrogate, $nC_{16}H_{34}$ as diesel surrogate



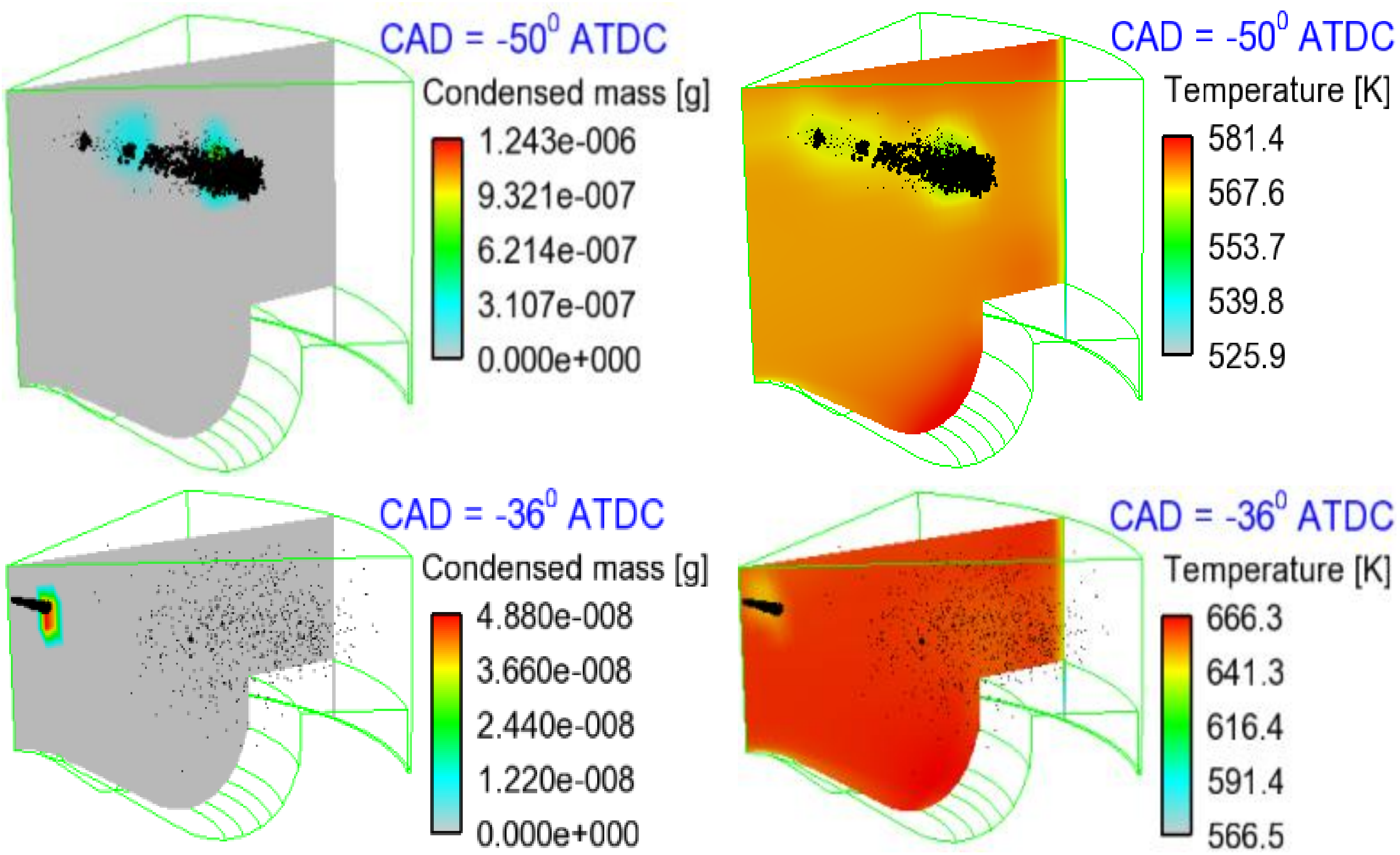
Modeling fuel condensation

Peng-Robinson EOS

$$P = \frac{R_u T}{v - b} - \frac{a}{v(v+b) + b(v-b)}$$

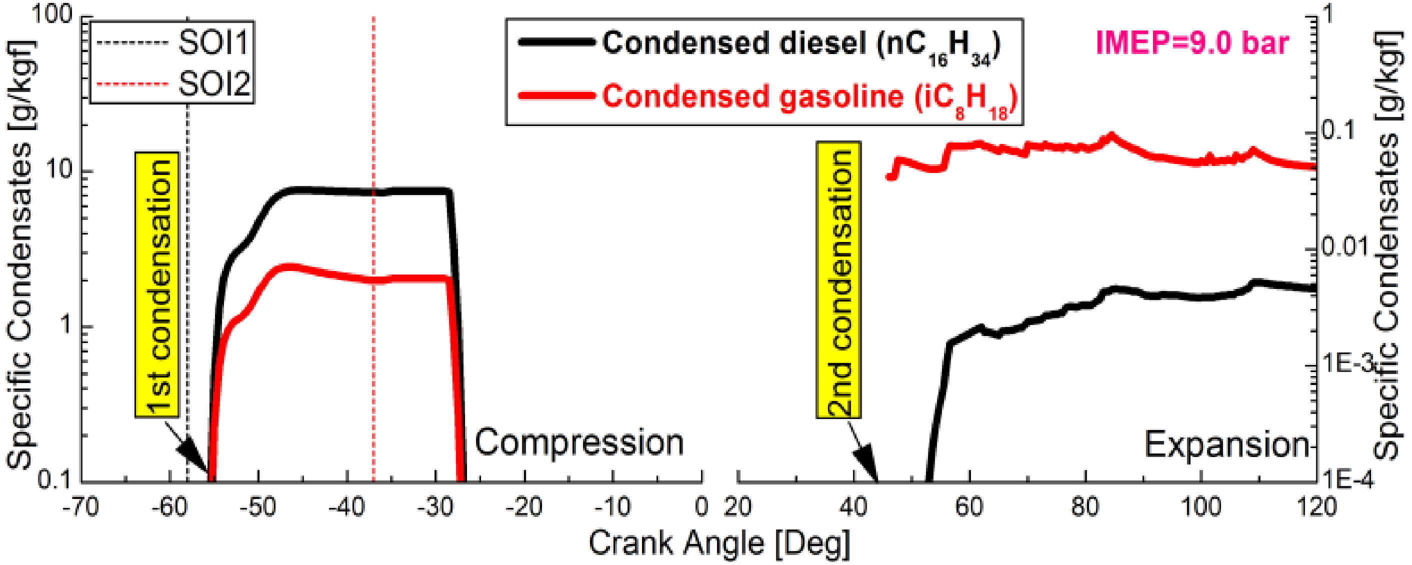


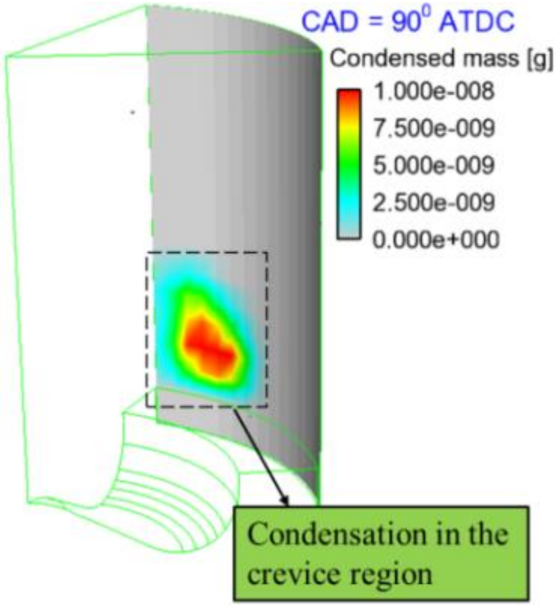
RCCI fuel injection - 9bar IMEP



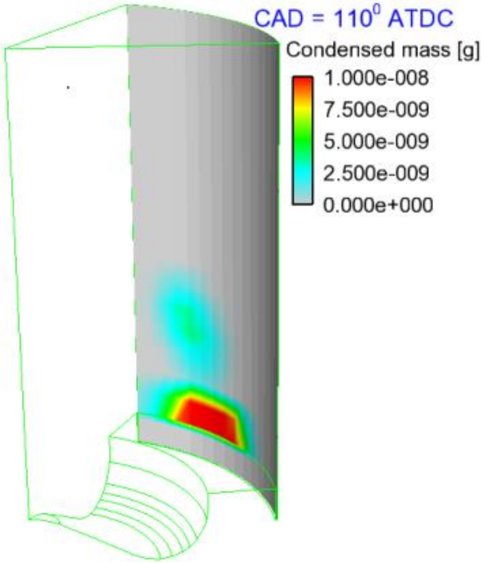
Double injection RCCI – fuel condensation predicted within sprays

Qiu, 2014

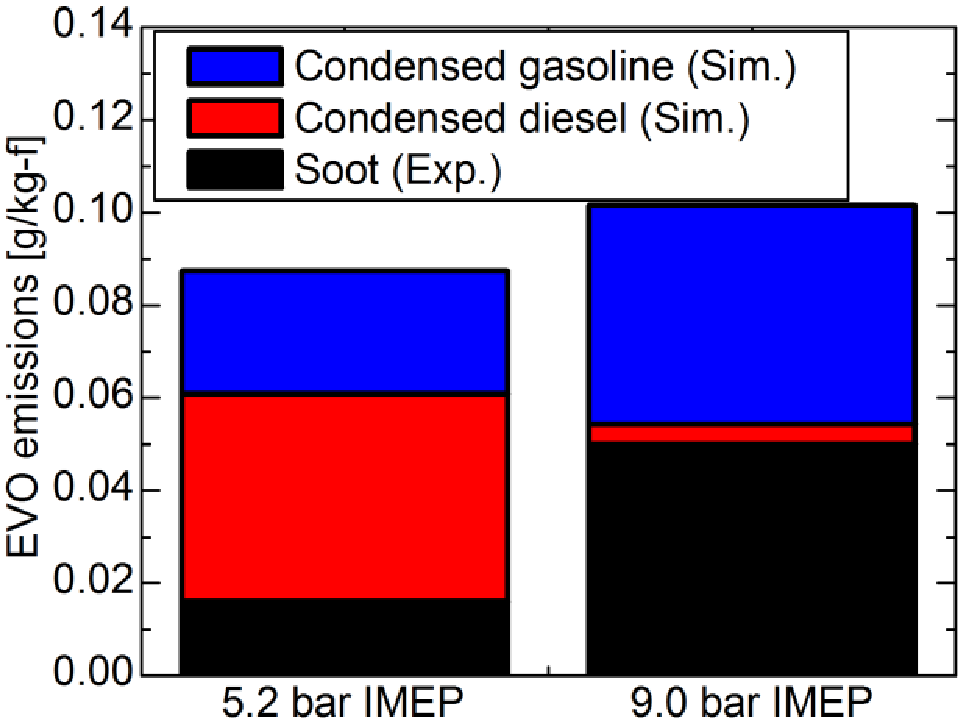




Condensation in the crevice region



RCCI particulate – predicted condensed fuel and soot at EVO



Fuel condensation in **RCCI** is predicted to play an important role in PM formation.

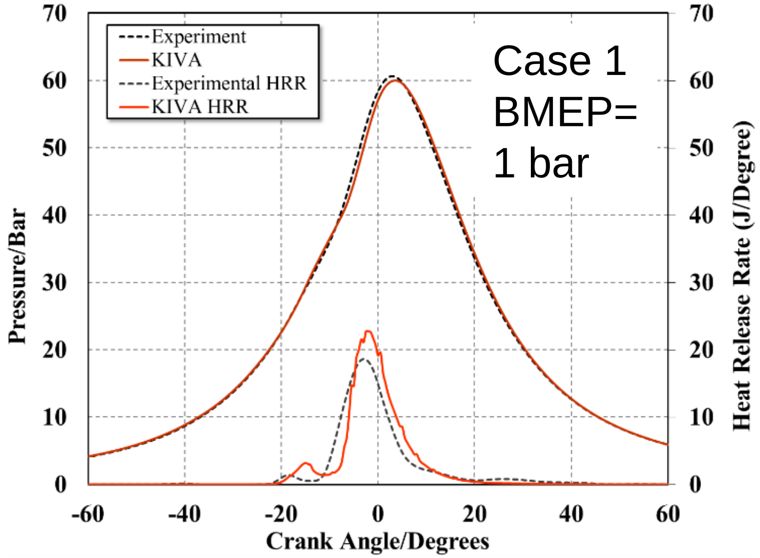
At low load (5.2 bar IMEP), about 90% of the PM is composed of condensed fuel.

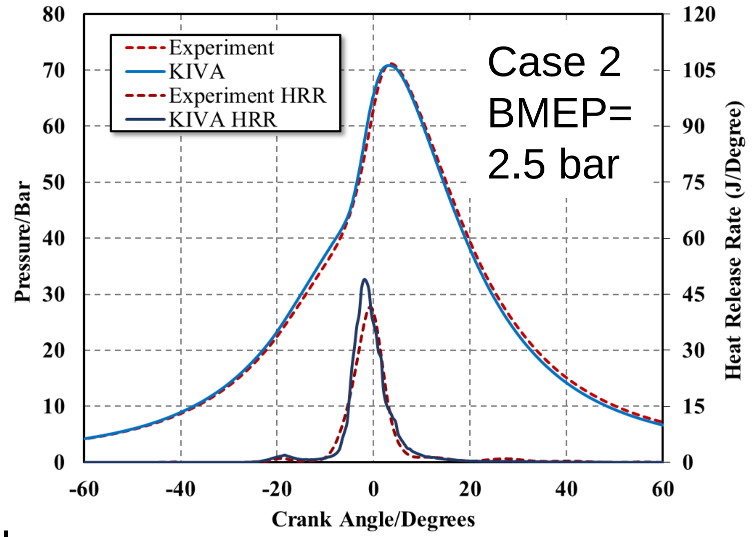
At higher load (9.0 bar IMEP), only about 50% of the engine-out PM is composed of condensed fuel, of which 90% is from the premixed gasoline.

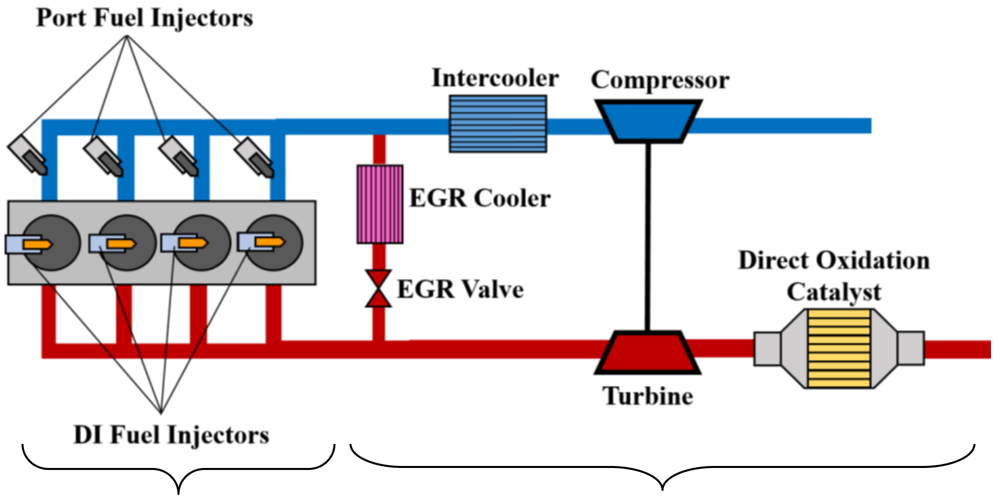
Bharath, 2014

VVT to improve LTC catalyst efficiency

	Case 1	Case 2
Intake Manifold Pressure/Bar	1.006	1.02
Fuel Energy/J	275.1	393
Engine Speed/RPM	1,500	
Gasoline Quantity (mg/cyl/cyc)	3.525	6.321
Diesel Quantity (mg/cyl/cyc)	2.619	2.482
Gasoline Start of Injection/Deg.	-227.36	
Diesel Start of Injection/Deg.	-40	-42
Diesel Fuel Rail Pressure/Bar	400	
EGR Fraction (%)	49.9	44.9





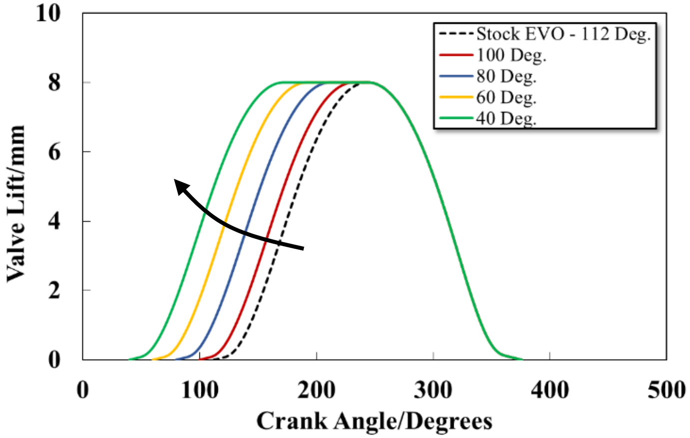


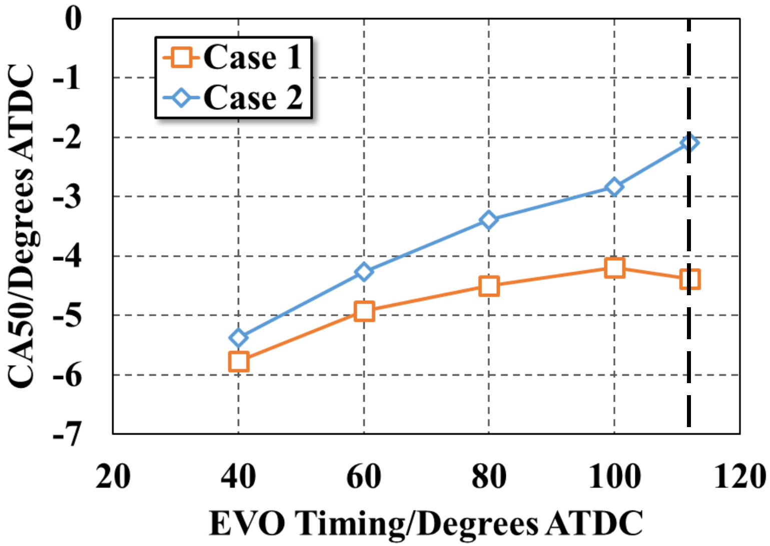
Modeled with KIVA

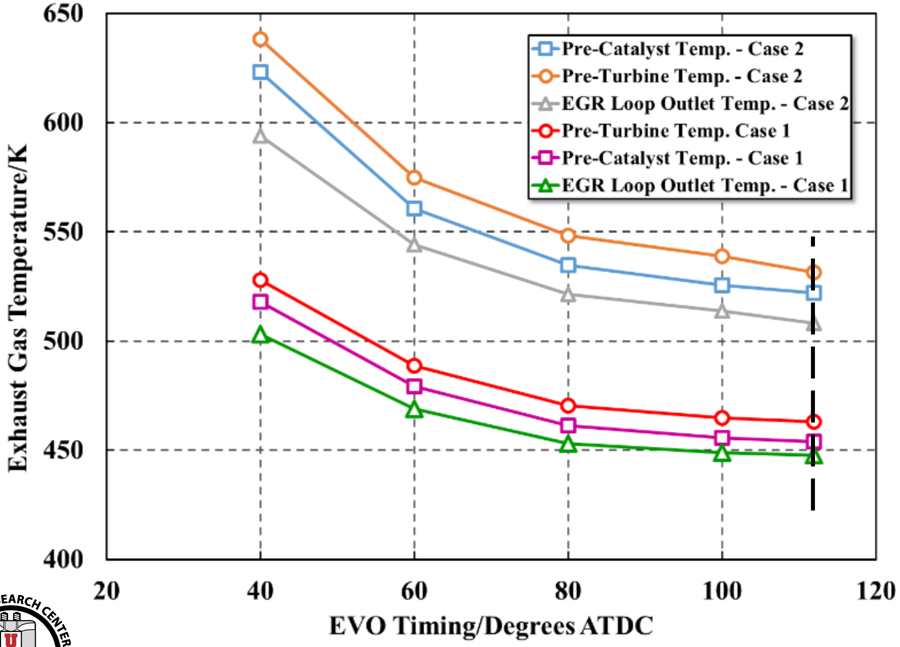
Modeled with GT-Power and Sampara and Bissett DOC model

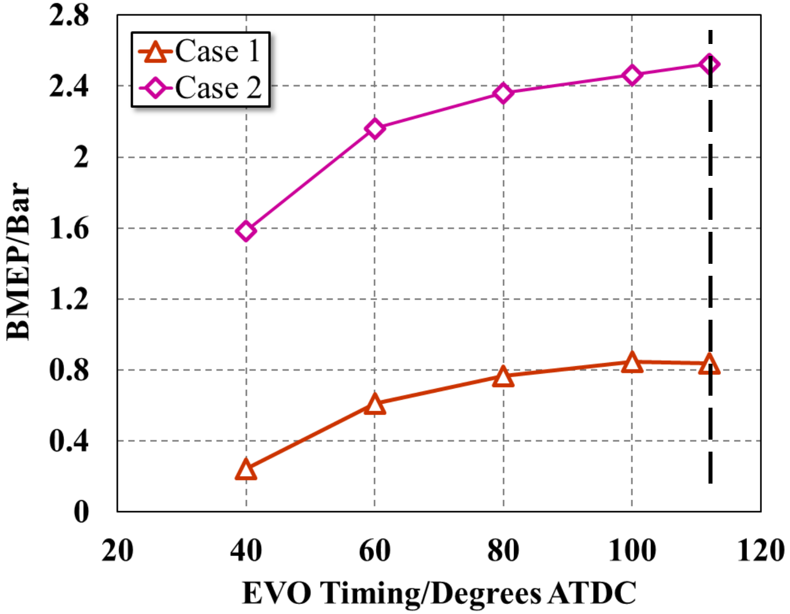
Bharath, 2014

VVT to improve LTC catalyst efficiency

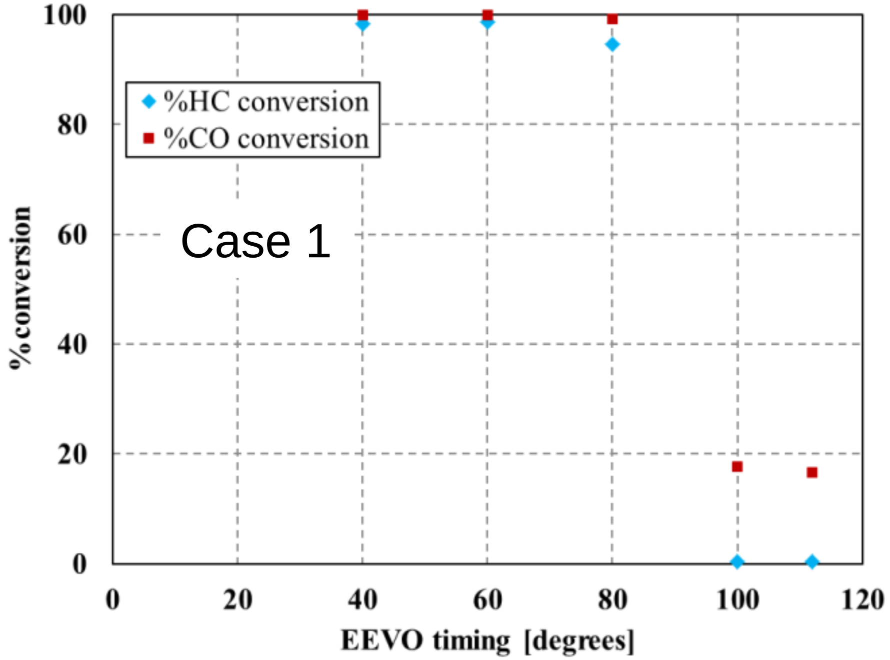








Use of VVT - DOC performance

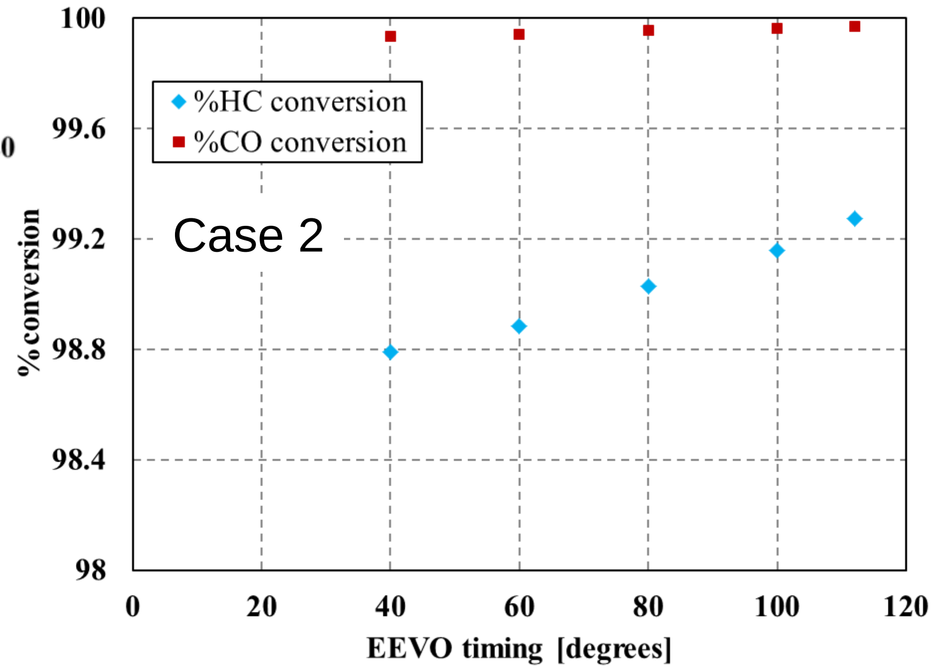


Higher exhaust temperatures with early EVO very beneficial in improving after-treatment efficiency at low load, since exhaust temperatures high enough to activate the catalyst.

UHC and CO conversion by the DOC Predicted to reach almost 100%

Advancing EVO timing increases exhaust temperature, thus reducing EGR needed for same IVC temperature and pressure

- improves vol. eff.



Summary and conclusions

- Due to high cost, complexity, and increased fuel/fluid consumption associated with exhaust after-treatment, there is a growing need for advanced combustion development
- Desire for alternatives to petroleum for transportation that have potential for large scale production is growing
- Modify fuel's reactivity to allow sufficient premixing of fuel & air prior to auto-ignition
  - → High octane fuels like gasoline, natural gas or alcohols
- Challenges with stability, ***controllability***, combustion efficiency, and pressure rise rates
- **Homogeneous Charge Compression Ignition (HCCI)**
  - Advantages: Simple/inexpensive, ultra-low NOx and soot
  - Challenges: High pressure rise rates and lack of direct cycle-to-cycle control over combustion timing
- **Partially Premixed Combustion (PPC)**
  - Advantages: DI injection timing and PFI/DI fuel split → mechanism for control
  - Challenges: Lack of Φ-sensitivity for gasoline-like fuels at low pressures
- **Reactivity Controlled Compression Ignition (RCCI)**
  - Advantages: In-cylinder blending of fuel reactivity broadens HR duration and allows global fuel reactivity to be changed. DI injection timing & global fuel reactivity → mechanism for control
  - Challenges: Consumer acceptance of requiring two fuel tanks