# Diesel Oxidation Catalyst Control of PM, CO and HC from Reactivity Controlled Compression Ignition Combustion


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***U.S. Department of Energy***



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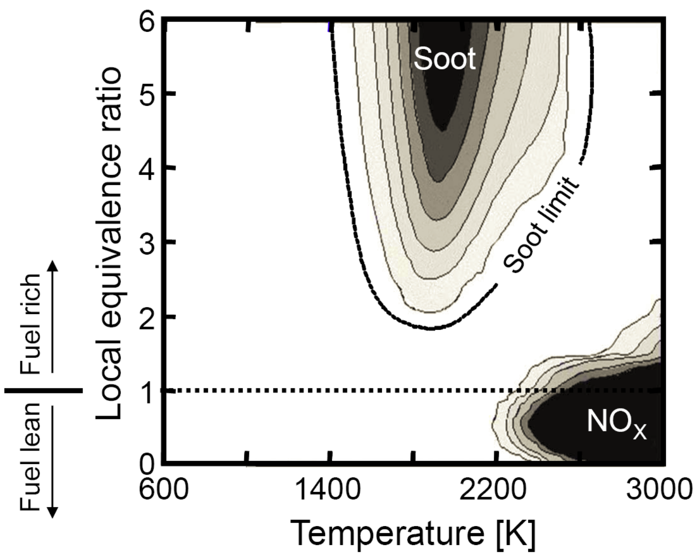
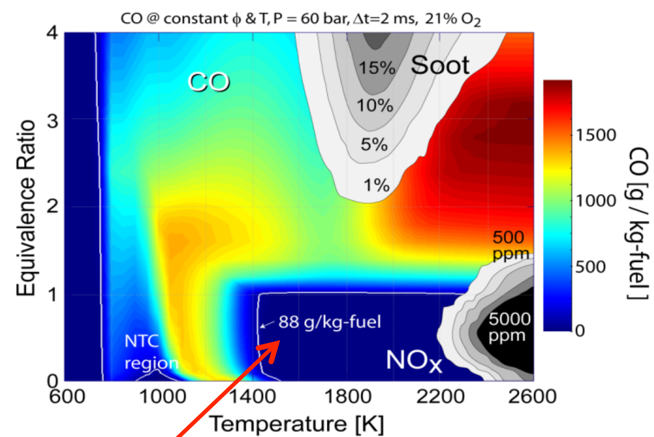
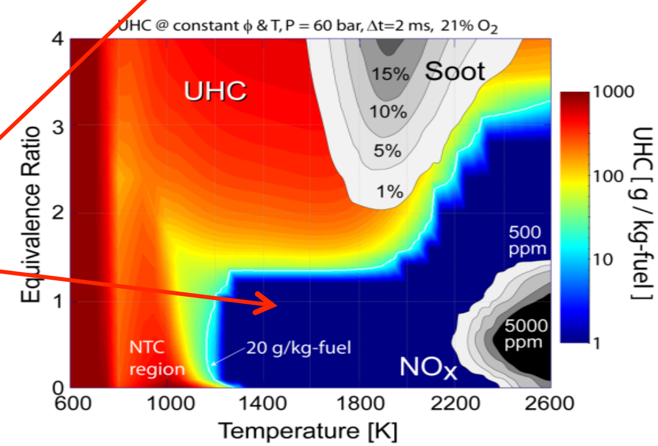
# Precise control of the combustion process allows for high efficiency and low emissions

**LTC creates reacting mixtures in-cylinder that avoid soot and NOx formation …**




**…while at the same time avoid CO and UHC emissions.**




**Charge must end up in this region after combustion is complete**

***Slide adapted from DOE presentation, Gurpreet Singh et al.***

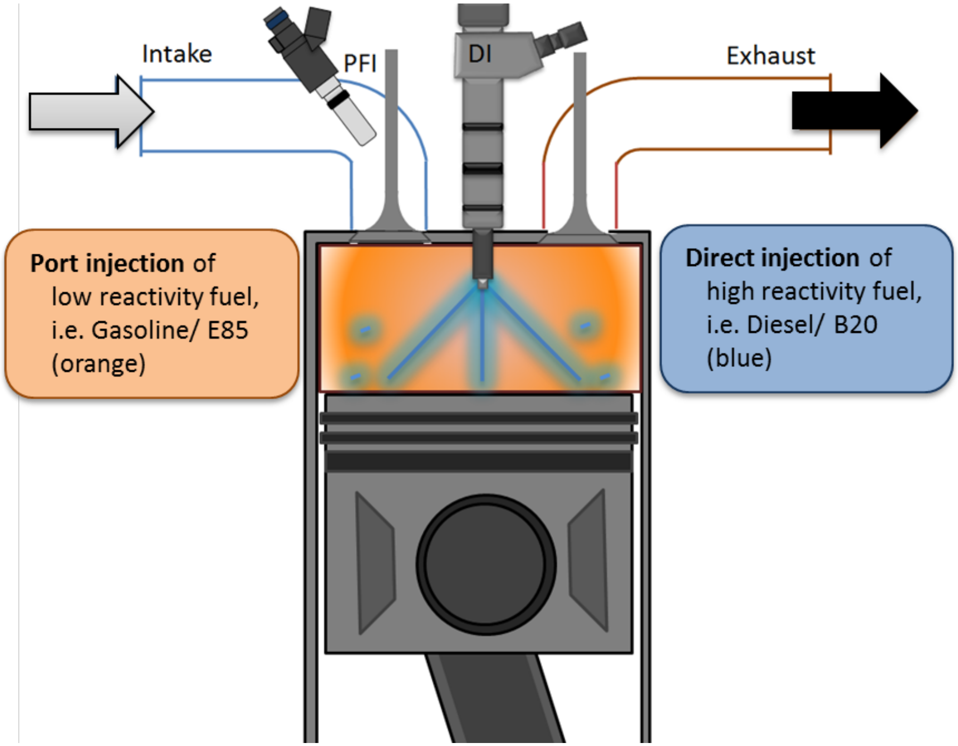
# Dual-fuel Reactivity Controlled Compression Ignition (RCCI)

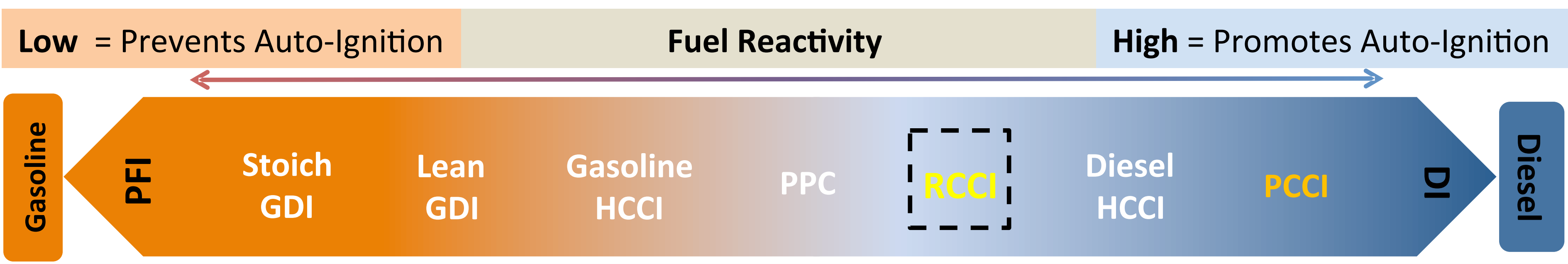
**RCCI allows increased engine operating range for premixed combustion through:**

- Global fuel reactivity (phasing)
- Fuel reactivity gradients (pressure rise)
- Equivalence ratio stratification
- Temperature stratification

**RCCI offers both benefits and challenges to implementation of LTC**

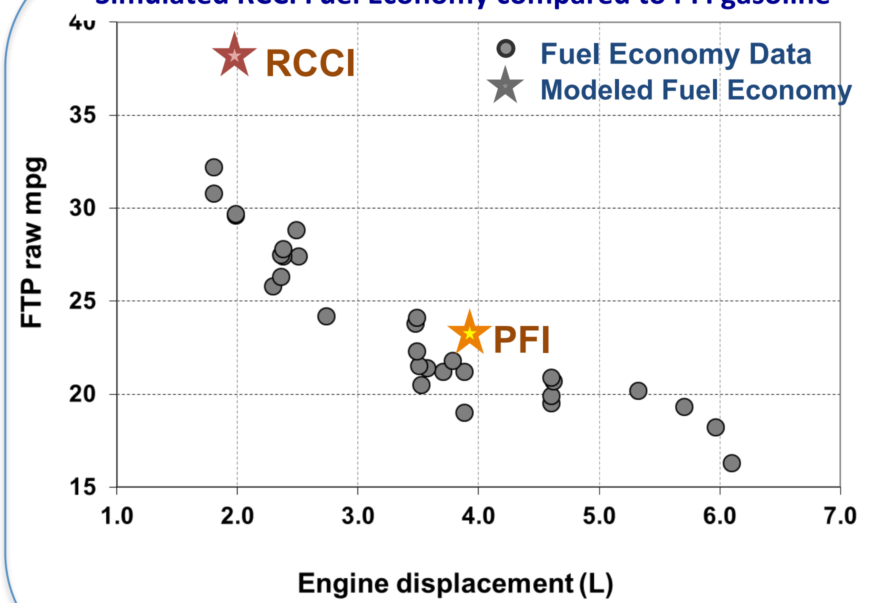
- Diesel-like efficiency or better
- Low NOx and soot
- Controls and emissions challenges



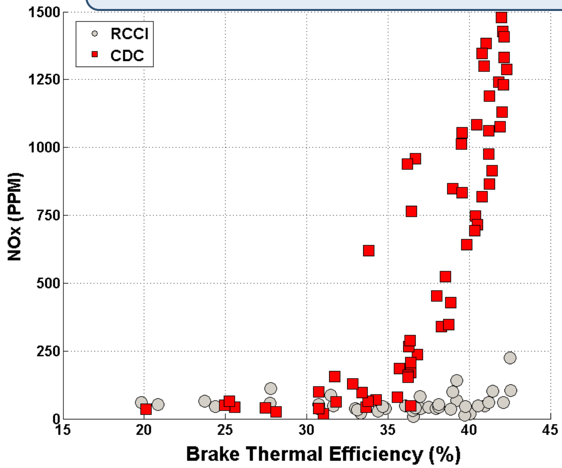
# Diesel-like (or better) efficiency with reductions in both NOx and PM

- **Peak BTE within light-duty drive cycle range (better than peak BTE of 1.9L GM diesel)**
- **Has the potential to improve fuel economy by 15% over best-in-class PFI**

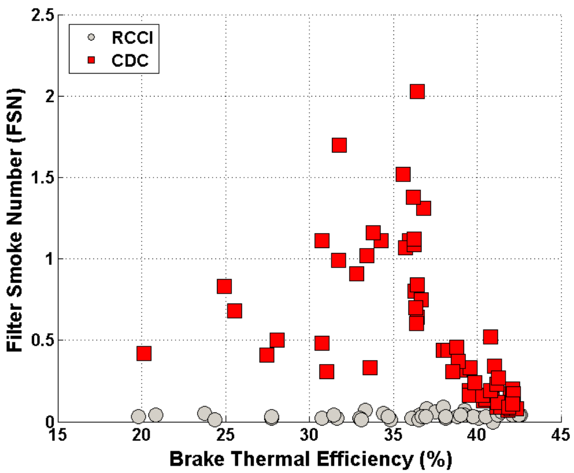



*Data for small to full-size passenger cars with varying vehicle weight*

**Low NOx across BTE**




**Near zero smoke number (not zero PM)**



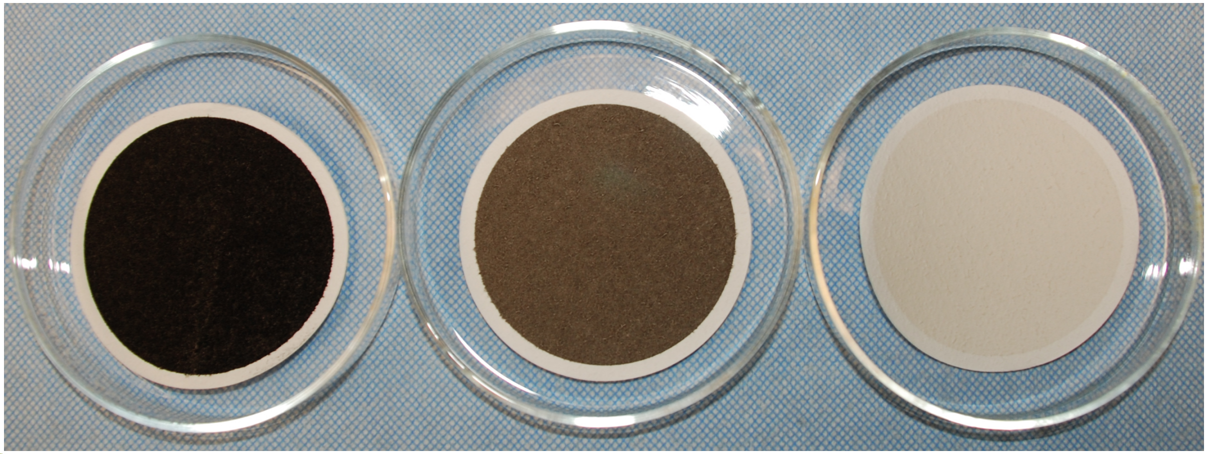

*Data from Curran et al will be presented at 2013 SAE World Congress*

# RCCI PM with uniquely different morphology and chemistry

- **Lack of appearance of black carbon in RCCI suggests differences in chemical composition**
- **Qualitative comparison of similar masses → RCCI particles shown to be mostly organic rather than elemental carbon**

**Engine Condition: 2300 rpm, 4.2 bar BMEP**

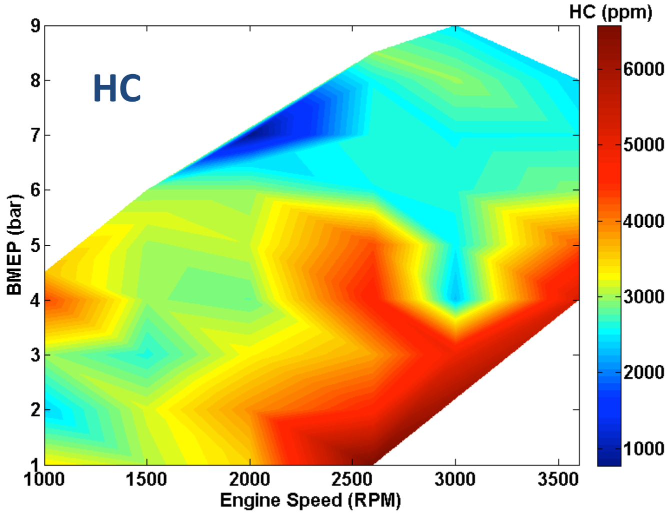
| | Conventional | PCCI | RCCI |
|---|---|---|---|

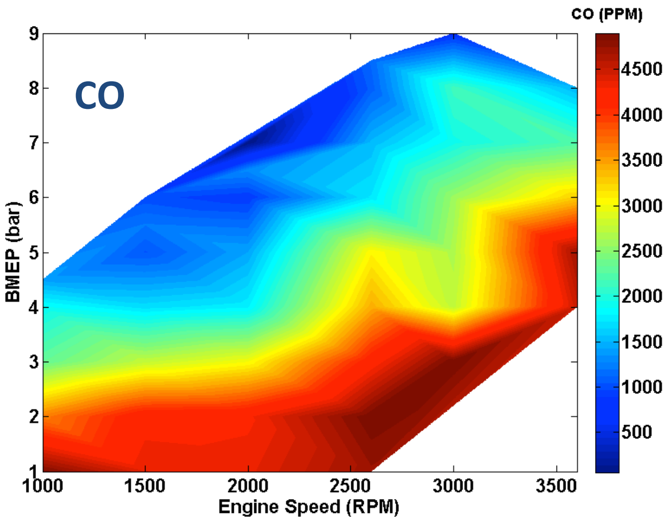


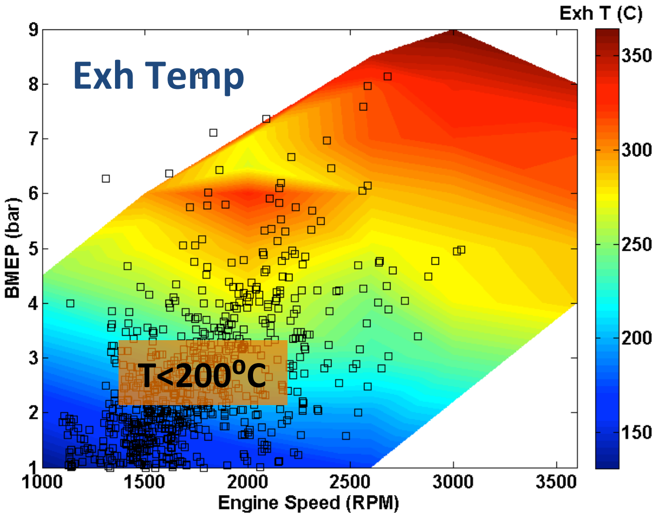
| | Conventional | PCCI | RCCI |
|---|---|---|---|
| PM Mass (mg/min)* | 0.137 | 0.025 | 0.040 |

*SAE 2010-01-2266*

# Gasoline-like HC and CO emission levels but at much lower exhaust temperatures

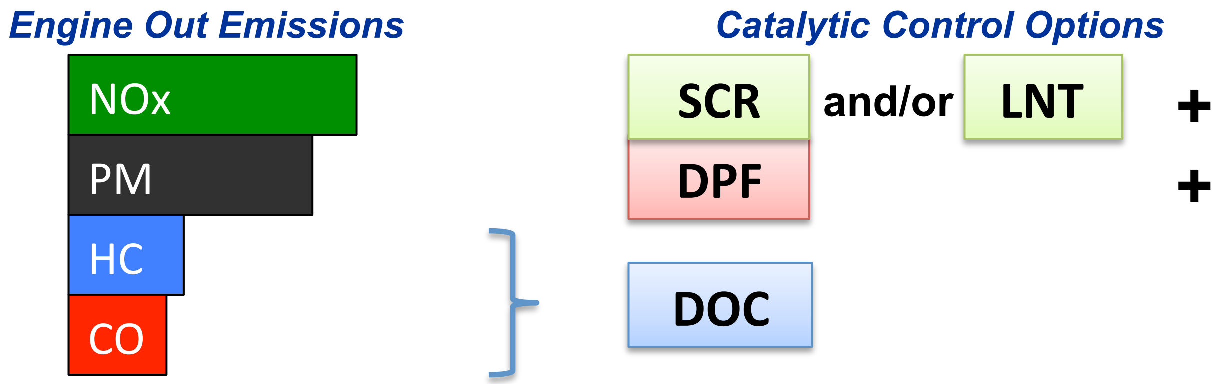


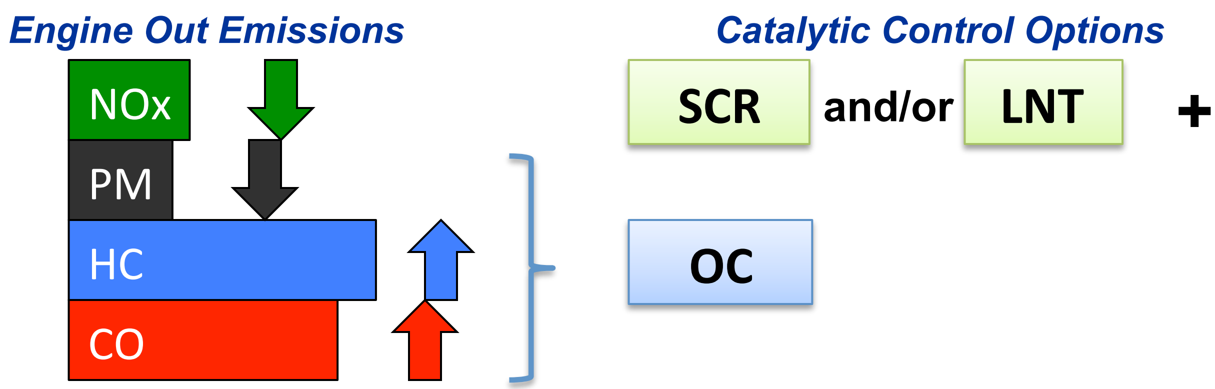



# RCCI presents different emission challenges

**Conventional Diesel**




**RCCI**



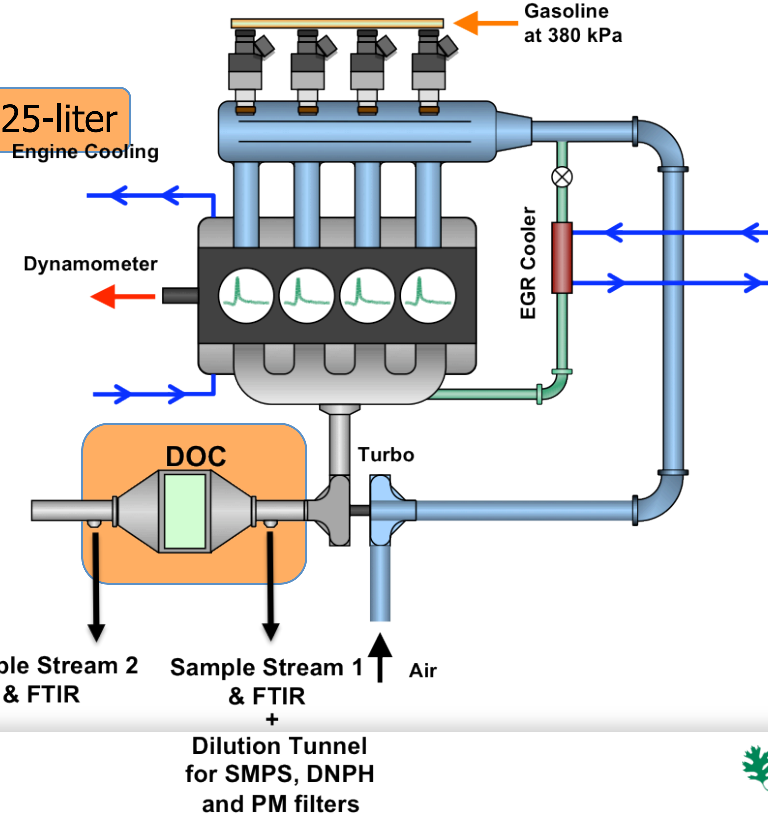
# Effectiveness of a DOC to control PM, CO and HC from RCCI

- **RCCI engine based on 2007 GM 1.9-L multi-cylinder diesel engine**
  - Dual-fuel system with PFI injectors for gasoline
  - OEM diesel fuel system
  - OEM variable geometry turbocharger
- **DRIVVEN control system with DCAT**
  - Full control of diesel & gasoline fuel systems
  - Cylinder-to-cylinder balancing capability
- **Exhaust aftertreatment**
  - Model DOC 100 g/ft$^3$ Pt, 1.25-liter

*ORNL Multi-Cylinder 1.9L GM CIDI*

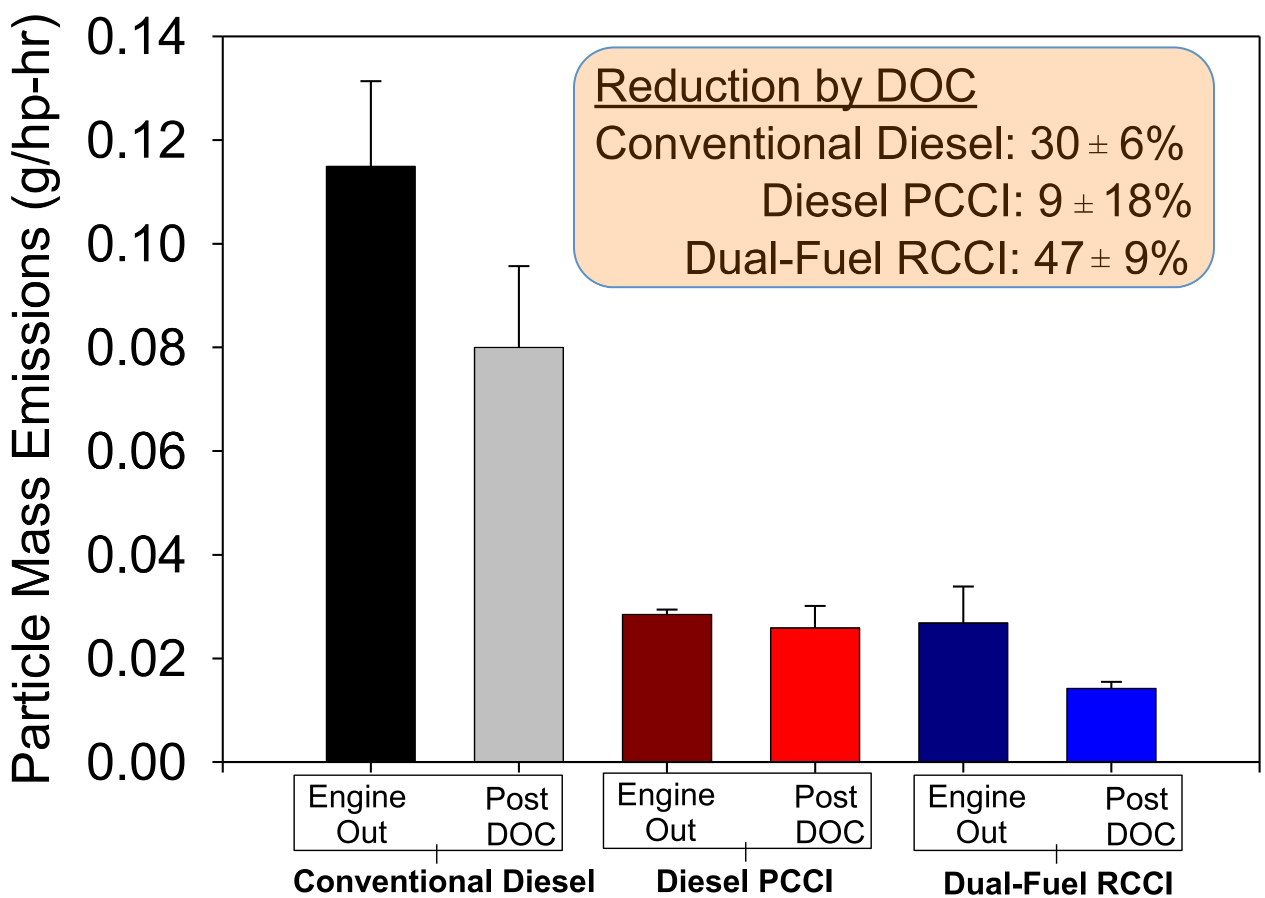
| Number of Cylinders | 4 |
|---|---|
| Bore, mm | 82.0 |
| Stroke, mm | 90.4 |
| Compression Ratio | 17.5 |
| Rated Power, kW | 110 |
| Rated Torque, Nm | 315 |

*Modified Intake Manifold with PFI Injectors*



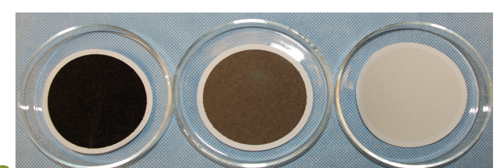
# RCCI PM mass reduced by ~50%

**Engine Condition: 2300 rpm, 4.2 bar BMEP**




**RCCI post-DOC emissions 0.014 ± 0.001 g/hp-hr**

- **Engine-out PCCI and RCCI mass are similar in magnitude but…**
  - 10% PM mass reduction in PCCI compared to 50% in RCCI
- **DOC effective despite low RCCI exhaust temperature**
  - Conventional: 411°C
  - PCCI: 408°C
  - RCCI: 247°C

| | Conv | PCCI | RCCI |
|---|---|---|---|
| |  | | |
| PM Mass (mg/min)* | 0.137 | 0.025 | 0.040 |



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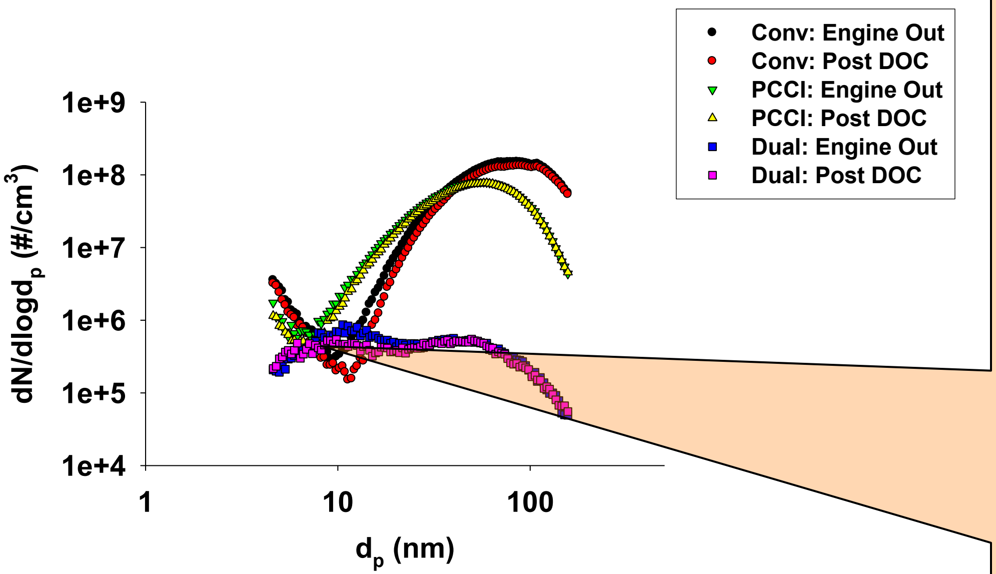
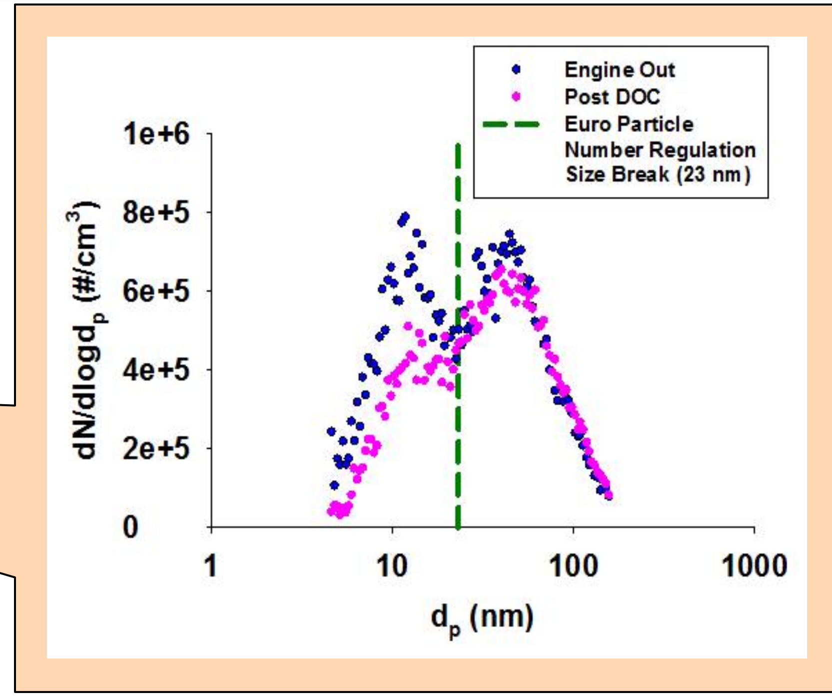
# RCCI PM Nuclei mode number concentration reduced 35 ± 6% by DOC



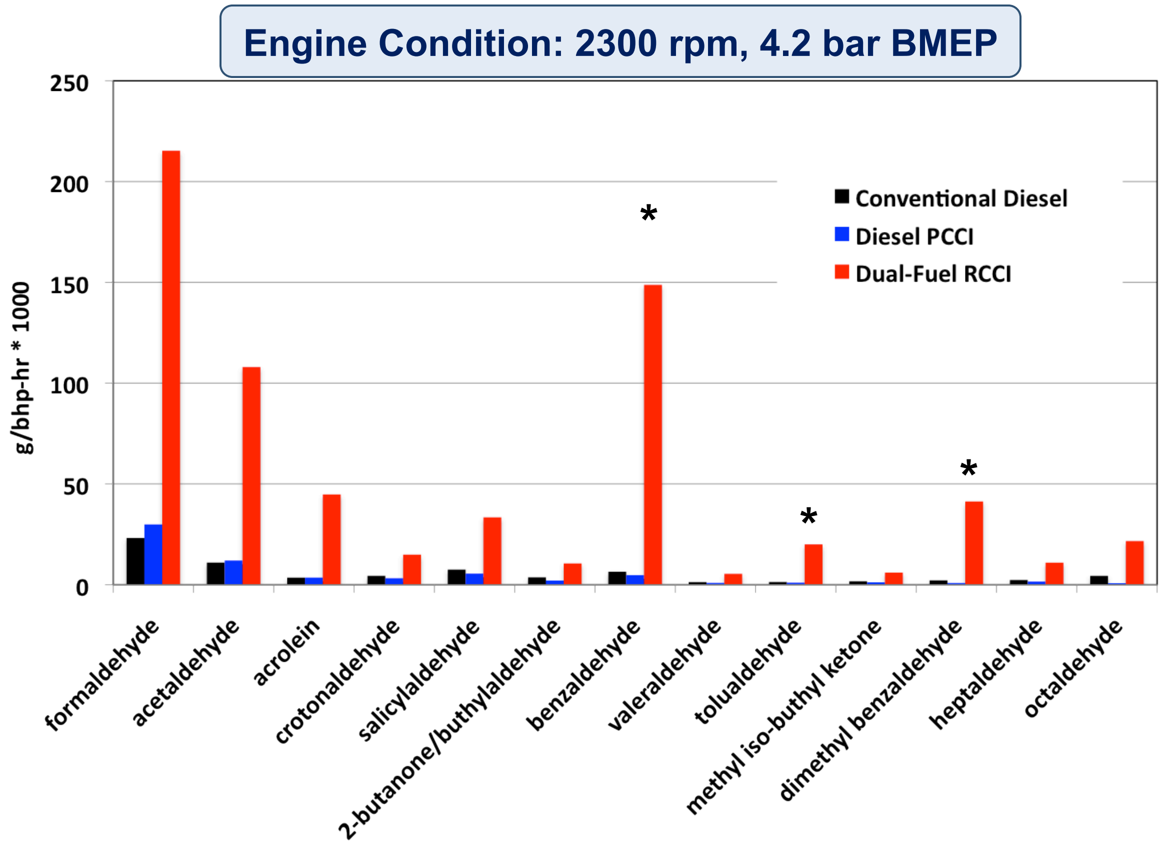




- **RCCI accumulation mode (>30 nm) ~100 times less than Conv and PCCI**
  - Enhanced fuel and air mixing
  - High HC concentration with lack of soot surface area for adsorption

**Nuclei mode is susceptible to vaporization and oxidation at 250 °C given high surface tension**

**Engine Condition: 2300 rpm, 4.2 bar BMEP**

# RCCI HC species are quite different from Conv. Combustion

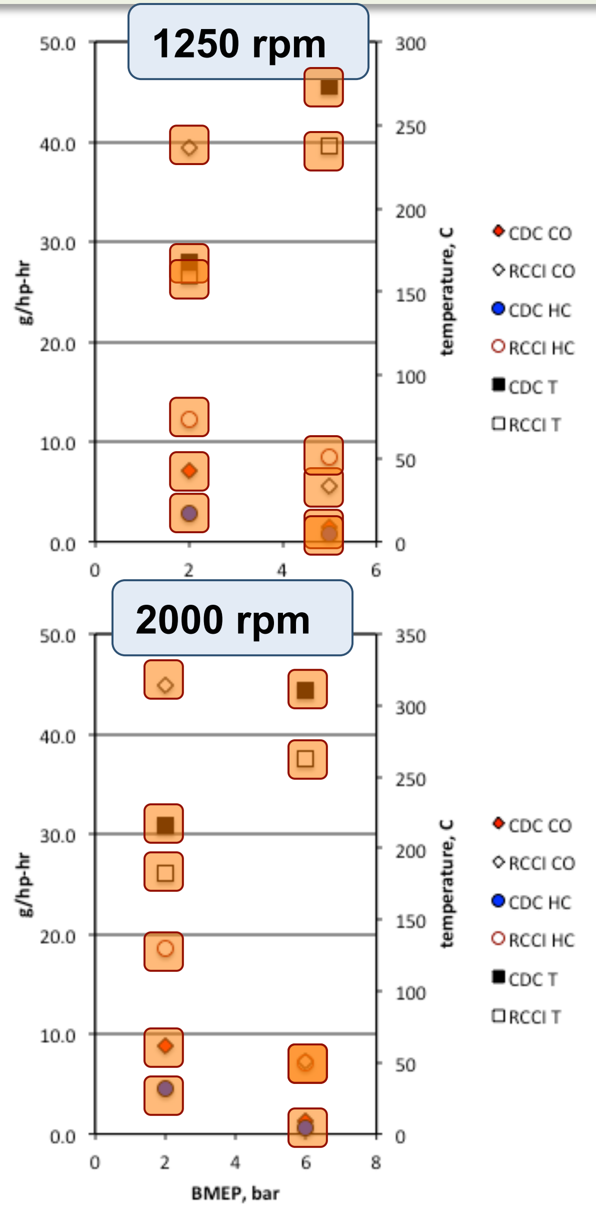



- **Considerable increase in carbonyl emissions for dual-fuel RCCI**
- **Disproportional increase in mono-aromatic carbonyls (Gasoline=mono-aromatic rich, diesel=mono-aromatic poor)**

**Gasoline to diesel ratio changes over the speed/load map, the chemical composition will shift from diesel-like to gasoline-like HCs and vice versa which may pose a challenge for a oxidation catalyst**

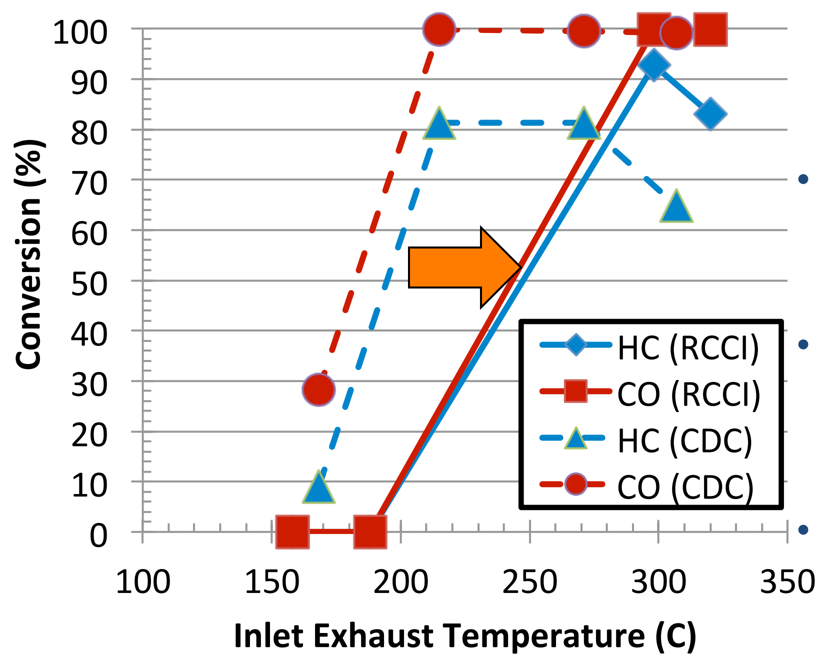
***SAE 2010-01-2266***

# RCCI results in shift in HC and CO light-off temperature




- RCCI engine out CO is 5x higher
- RCCI engine out HC is 4x at lower loads and 11 times at higher loads
- Lower exhaust temperatures

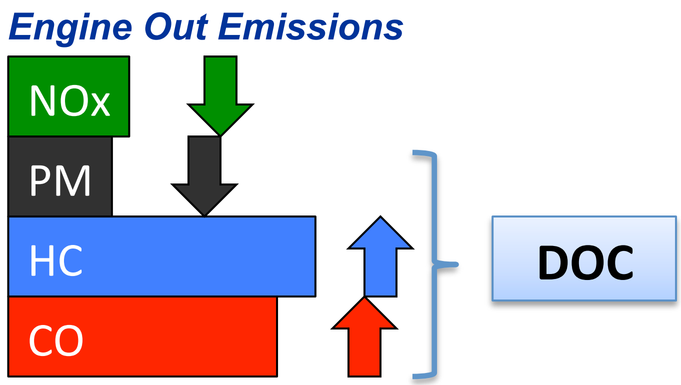
| Speed/Load rpm/bar | ΔT °C |
|---|---|
| 1250/2.0 | 8 |
| 1250/5.0 | 35 |
| 2000/2.0 | 34 |
| 2000/6.0 | 49 |




- 80% HC and 100% CO conversion at 190°C at conventional combustion
- No catalyst activity in RCCI below 200°C
- Shift to higher HC and CO light-off in RCCI

# Summary

RCCI




- **Significant reduction in engine out NOx and PM emissions**
- **Much higher CO and HC emissions**
- **Low exhaust temperatures (much <200°C)**

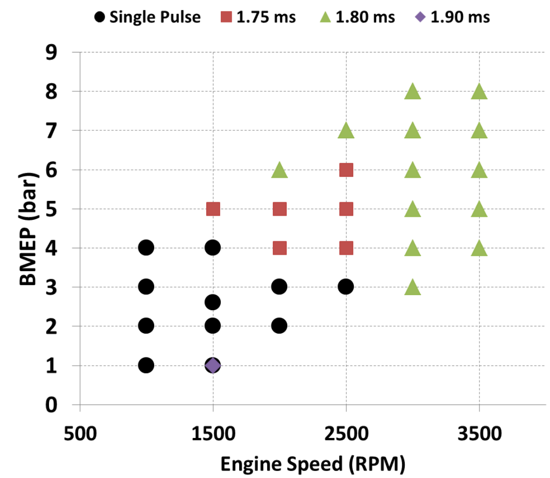
- **50% reduction in PM by DOC at 250°C**
- **Shift to higher HC and CO light-off in RCCI**
  - No DOC activity below 200°C and near complete CO and HC removal above 300°C compared to 80% HC and 100% CO conversion at 190°C at conventional combustion

# RCCI Mapping Data is available at CLEERS website

- **Efficiency and emissions map of gasoline and diesel RCCI**
- **http://www.cleers.org/databases/filepage.php?fileid=30**

CLEERS Database

http://www.cleers.org/databases/




| BMEP (bar) | Speed (RPM) | Torque (ft-lb) | Diesel Rate (g/s) | Gasoline rate (g/s) | Max COV (%) | Gas % (mass) | BTE (%) | Raw BSFC (g/kwhr) | D_eq BSFC (g/kwhr) | BaroP (InHg) | AirMassFlow (g/s) | EGR Rate (%) | | AFR mass | HC (ppm) | NOx (ppm) | CO (ppm) | CO2 Intake (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 1000 | 11.526 | 0.1537 | 0.04770 | 10.4 | 0.2369 | **18.90** | 443.0 | 443.4 | 28.91 | 15.91 | 4.53 | 0.05 | 79.00 | 1992.3 | 26.84676 | 5086.4 | 0.096 |
| 2.0 | 1000 | 22.772 | 0.1240 | 0.15309 | 2.8 | 0.5525 | **27.11** | 308.5 | 309.2 | 28.91 | 15.90 | 3.51 | 0.05 | 57.37 | 2882.1 | 10.24139 | 5244.6 | 0.105 |
| 3.0 | 1000 | 34.429 | 0.0930 | 0.25252 | 4.0 | 0.7309 | **32.85** | 254.4 | 255.1 | 29.05 | 15.42 | 2.85 | 0.03 | 44.63 | 3225.4 | 7.471395 | 2010.4 | 0.113 |
| 4.0 | 1000 | 45.384 | 0.1193 | 0.33133 | 1.5 | 0.7352 | **33.19** | 251.8 | 252.5 | 28.91 | 16.06 | 4.29 | 0.07 | 35.64 | 3228.0 | 16.59825 | 1412.8 | 0.237 |
| 1.0 | 1500 | 11.97972 | 0.1906 | 0.13741 | 5.7 | 0.4189 | **18.08** | 462.8 | 463.6 | 28.93 | 23.25 | 3.25 | 0.04 | 70.89 | 3630.9 | 21.92095 | 5015.9 | 0.065 |
| 2.0 | 1500 | 22.973 | 0.2111 | 0.22608 | 4.2 | 0.5171 | **26.00** | 321.7 | 322.3 | 28.93 | 22.73 | 2.10 | 0.05 | 52.00 | 3034.6 | 27.03704 | 4845.1 | 0.065 |
| 2.6 | 1500 | 29.609 | 0.2365 | 0.27792 | 4.0 | 0.5403 | **28.48** | 293.6 | 294.3 | 28.92 | 22.87 | 1.78 | 0.01 | 44.47 | 2852.7 | 9.790642 | 3579.5 | 0.069 |
| 4.0 | 1500 | 45.495 | 0.1550 | 0.50697 | 2.4 | 0.7659 | **33.97** | 245.9 | 246.7 | 28.92 | 24.67 | 1.75 | 0.02 | 37.26 | 3118.1 | 12.51186 | 1834.2 | 0.088 |