Fuel Effects on RCCI Combustion: Performance and Drive Cycle Considerations

Scott Curran, Zhiming Gao, Jim Szybist, and Robert Wagner

Oak Ridge National Laboratory

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Combustion will be an important part of the solution with end game objective to maximize vehicle efficiency with compliant emissions. Charge must end up in this region after combustion is complete ...while at the same time avoiding CO and UHC emissions.

Need to manage the combustion process to avoid soot and NOx formation ...

Adapted from DOE presentation, Gurpreet Singh et al.

SI

PPC

RCCI

CIDI

Fuel Reactivity

Low = Prevents Auto-Ignition

High = Promotes Auto-Ignition

Backup Slide for LTC Landscape
Reactivity Controlled Compression Ignition – Dual-Fuel Partially Premixed Combustion Technique

- Reactivity controlled compression ignition (RCCI) allows increased heat-release control
  - A low-reactivity fuel is introduced early and premixed with air
  - A high-reactivity fuel is injected into the premixed charge before ignition

- RCCI increases engine operating range for premixed combustion
  - Global fuel reactivity (phasing)
  - Fuel reactivity gradients (pressure rise)
  - Equivalence ratio and temperature stratification

- RCCI offers both benefits and challenges to implementation of LTC
  - Diesel-like efficiency or better
  - Ultra-Low NOx and soot
  - Controls and emissions challenges

Port injection low reactivity fuel, i.e. Gasoline/ E85 (orange)
Direct injection high reactivity fuel, i.e. Diesel/ B20 (blue)
Advanced combustion modes must match with the LD-drive cycles to have maximum improvement on fuel economy and emissions

- Emissions regulations and fuel economy for light-duty vehicle are prescribed over transient drive cycles (EPA Federal Driving Schedules)
- Emissions standards are set by EPA for criteria air pollutants
  - NO\textsubscript{x}, NMOG, CO, PM

  Steady state advanced combustion brake efficiency emissions from steady state points do not directly equate to drive cycle performance (i.e. fuel economy and emissions)

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**Urban Dynamometer Driving Cycle**

Commonly called the "LA4" or "the city test" and represents city driving conditions

**Highway Fuel Economy Test**

Represents highway driving conditions under 60 mph

**US06**

High acceleration aggressive driving schedule – one of two "Supplemental FTP“ tests

**SC03 80 MPH**

FTP with Air Conditioner driving schedule – one of two "Supplemental FTP” tests
ORNL’s comprehensive approach to advanced combustion research includes fuel effects and engine system integration

- **2007 GM 1.9-L multi-cylinder diesel engines**
  - OEM (CR 17.5) and **modified RCCI** pistons (CR 15.1) (backup slide)
  - Dual-fuel system with PFI injectors
  - OEM diesel fuel system with DI injectors
  - Microprocessor based control system

- **Aftertreatment integration & emissions characterization**
  - Modular catalysts / regulated and unregulated emissions
  - Particulate matter characterization

- **Vehicle systems simulations using Autonomie**
  - Experimental engine maps used for drive cycle simulations
  - Comparison between 2009 PFI, diesel and diesel/RCCI
  - Multi-mode (RCCI to conventional diesel combustion) used for areas of the drive cycle outside the RCCI operating range

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1 Autonomie, Developed by Argonne National Lab for U.S. DOE, [http://www.autonomie.net/](http://www.autonomie.net/)
Current RCCI Operation Includes Most of Light-Duty Drive Cycle

- RCCI mapped with focus on efficiency and lowest possible emissions
  - Peak BTE within light-duty drive cycle range (better than peak BTE of 1.9L GM diesel)

- Detailed RCCI map shows insights into future development opportunities and challenges
  - Aftertreatment integration (low exh T), drive cycle simulations (load coverage)
  - Load expansion challenges are under investigation for maximizing BTE
  - Cyclic dispersion, exhaust residuals, thermodynamic analysis of loss mechanisms
Unique properties of biofuels can be taken advantage of for dual-fuel RCCI operation

- Commercially available biofuels replacements for both the PFI fuel and DI fuel were found to have properties that enable load expansion in RCCI.
- Biofuels allows for improved efficiency through RCCI load expansion and direct petroleum displacement through substitution.
- Load expansion to cover the entire drive-cycle operating map with high efficiency and low NOx and Soot is also important for addressing market barriers to eventual LTC implementation.

Ethanol blends

- Allow for load expansion through combination of increased Octane, charge cooling and radical sinking

Biodiesel Blends

- Biofuels allows for increased ratio of PFI fuel to DI fuel without sacrificing emissions or stability

Combination of the two offers additional benefits

Backup Slides for Details on B20 and Ethanol Blends
RCCI Mapping Completed w/ Multiple Fuel Combinations

- RCCI mapped with focus on efficiency and lowest possible emissions (Q3 Joule Milestone)
  - Self imposed constraints of pressure raise rate (10bar/deg upper load) and CO limit (5000 PPM lower load)
- Current RCCI map requires mode-switching to cover light-duty drive cycles
  - 100% coverage of low-temperature combustion is necessary to avoid mode-switching (RCCI to CDC) and additional emissions controls which would have negative impacts on fuel economy and costs

High load notes
Constraint on MPRR and combustion noise
High load increased compared to previous maps resulting in possible fuel efficiency gains
Further development opportunities

Low load notes
CDC used for lower engine loads due to similar efficiencies and NOx with much lower HC and CO than RCCI (Very low NOx CDC in this range ~ PCCI like)

Emissions concerns
- Not able to achieve lower NOx than CDC without sacrificing BTE
- Sub 200°C exhaust temps with high HC and CO represents clear challenges with current oxidation catalysts
Biofuel blends potential path to enabling low temperature combustion

**Motivation**

- 100% coverage of low temperature combustion is necessary to avoid mode-switching and additional emissions controls which would have negative impacts on fuel economy and costs

* Mixed mode LTC RCCI and PCCI may be required
Biofuel blends potential path to enabling low temperature combustion

- Motivation
  - 100% coverage of low temperature combustion is necessary to avoid mode-switching and additional emissions controls which would have negative impacts on fuel economy and costs

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<th>Drive Cycle Coverage (non-idling)</th>
<th>B20/UTG</th>
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<td>UDDS</td>
<td>72%</td>
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<tr>
<td>HWFET</td>
<td>88%</td>
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</tbody>
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* Mixed mode LTC RCCI and PCCI may be required
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<th>B20/UTG</th>
<th>ULSD/E30</th>
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</thead>
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<tr>
<td>UDDS</td>
<td>72%</td>
<td>52%</td>
</tr>
<tr>
<td>HWFET</td>
<td>88%</td>
<td>74%</td>
</tr>
</tbody>
</table>

* Mixed mode LTC RCCI and PCCI may be required
Current RCCI map requires mode-switching to cover light-duty drive cycles

- Fuel Economy Improvement depends on drive-cycle coverage and BTE difference
  - With multi-mode operation, low load RCCI is important for % cycle coverage but requires high BTE delta to increase fuel economy and to make up for high HC/CO and low Exhaust temps

Backup Slide for Details on Each Simulation Comparison
RCCI – Challenges Include Lower Exhaust Temps with High HC/CO emissions

**High HC and CO**
- Similar to PFI engine out
- Gasoline range and diesel range species with increased aldehydes etc...

**Low exhaust temperatures**
- Areas < 200° C

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**Back-up Slide Emissions Drive cycle simulations**
RCCI offers >20% fuel economy improvement all 2009 PFI engines evaluated

- PFI map matches 0-60 time of 1.9L diesel engine
  - 0-60 time matched to 2.7L vehicle with best fuel economy from 2.4L engine

- ORNL chassis dyno and EPA fuel economy data mined for other PFI engine sizes
  - Figure shows how city (UDDS/FTP) fuel economy trends with displacement
  - More complete comparison against best-in-class PFI engines

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RCCI % Fuel Economy Improvement

<table>
<thead>
<tr>
<th>Engine Size</th>
<th>1.8L</th>
<th>2.4L</th>
<th>2.7L</th>
<th>4.0L</th>
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<tbody>
<tr>
<td>UNIT</td>
<td>MPG</td>
<td>MPG</td>
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</tr>
<tr>
<td>UDDS</td>
<td>33.1%</td>
<td>31.1%</td>
<td>45.8%</td>
<td>59.2%</td>
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<tr>
<td>HWFET</td>
<td>41.6%</td>
<td>36.8%</td>
<td>45.7%</td>
<td>55.4%</td>
</tr>
<tr>
<td>US06</td>
<td>50.5%</td>
<td>38.4%</td>
<td>47.4%</td>
<td>38.2%</td>
</tr>
<tr>
<td>SC03</td>
<td>33.1%</td>
<td>27.7%</td>
<td>41.9%</td>
<td>52.0%</td>
</tr>
</tbody>
</table>

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

Backup Slide for Matching 0-60 Performance
Many renewable fuels have unique properties which can enable/expand high efficiency engine operation and improve performance as compared to conventional fuels.

Advanced combustion techniques such as RCCI can increase engine efficiency and lower NOx and PM emissions.

- **RCCI uses in-cylinder blending of two fuels with different fuel reactivity (octane/cetane) to allow increased control over combustion compared to other advanced combustion methods that use a single fuel**
  - Biodiesel blends lower pre-mixed ratio needed for meeting emissions and performance targets
  - Lower reactivity and charge cooling effects of ethanol allow for load expansion but can limit low load stability

- **RCCI offers increased control for adaptation of LTC modes to market variations in fuel**
  - The ability for RCCI to compensate for full range of market fuels has not been explored
  - Understanding of sensitivity to fuel effects will be critical in developing engine controls and emissions controls
Acknowledgements

Kevin Stork, Steve Przesmitzki, Gurpreet Singh, Ken Howden, and Leo Breton of the United States Department of Energy Vehicle Technologies Program for funding a significant portions of the research in this presentation.

Many, many contributors spanning the ORNL Sustainable Transportation Program including all of the Fuels, Engines and Emissions Research Center.
Contact
Scott Curran
curransj@ornl.gov, 865-946-1522
Recent References and Further Information


Modeled RCCI Drive Cycle Fuel Economy

- Modeling results show up to a 22 - 28% improvement in fuel economy with RCCI over UDDS compared to 2009 PFI baseline on same vehicle
  - RCCI fuel economy in diesel equivalent MPG

Modeled Fuel Economy Improvements with RCCI

<table>
<thead>
<tr>
<th>% Fuel Economy Improvement With RCCI</th>
<th>2009 PFI</th>
<th>Diesel 1.9L CIDI</th>
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</thead>
<tbody>
<tr>
<td>UDDS (city)</td>
<td>+ 31%</td>
<td>+ 10%</td>
</tr>
<tr>
<td>HWFET (highway)</td>
<td>+ 37%</td>
<td>+ 10%</td>
</tr>
<tr>
<td>US06 (high speed)</td>
<td>+ 38%</td>
<td>+ 6%</td>
</tr>
<tr>
<td>SCO3 (air cond FTP)</td>
<td>+ 28%</td>
<td>+ 8%</td>
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Modeling provides insight into fuel needs under mixed-mode RCCI operation
- Amount of drive cycle spent in RCCI mode
- Total amount of diesel fuel used (or secondary fluid)
- Fuel split during RCCI operation
Modeled RCCI Drive Cycle Fuel Economy –B20 Map

- Modeling results show up to a 59% improvement in fuel economy with RCCI over UDDS compared to 2009 PFI (SI) baseline on same vehicle (4.0L PFI baseline).

Modeled Fuel Economy Improvements

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<th>% Fuel Economy Improvement With RCCI</th>
<th>Vs. PFI</th>
<th>Vs. Diesel</th>
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<tr>
<td>UDDS (city)</td>
<td>+ 59%</td>
<td>+ 14%</td>
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<td>+ 53%</td>
<td>+ 15%</td>
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<td>+ 39%</td>
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<td>NY City (stop and go)</td>
<td>+ 67%</td>
<td>+ 13%</td>
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- RCCI fuel economy improvements despite lack of complete drive cycle coverage
  - Further development underway (fuels, hardware, controls)

- Results based on steady state engine data
  - Does not address transient operation

- Does not address aftertreatment effectiveness
  - On going research at ORNL

14% improvement over UDDS coverage allowed with biodiesel as compared to RCCI with gasoline and diesel fuel.
RCCI offers >20% improvement all 2009 PFI engines evaluated

- PFI map matches 0-60 time of 1.9L diesel engine
  - 0-60 time matched to 2.7L vehicle with best fuel economy from 2.4L engine

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1 Data for small to full-size passenger cars with varying vehicle weight
RCCI – High Efficiency with Low NOx and Soot

**Low NOx**
- Trade-off of BTE and ultra-low NOx
- Drive Cycle Simulations will reveal the level of NOx aftertreatment needed to meet Tier 2 Bin 5 and Bin 2 standards

**Near zero smoke number**
- Previous results show PM is also reduced
- Indicates very little elemental carbon in PM (Not zero PM)
- Implications for possible effectiveness of DOC to further reduce PM
Biodiesel blends allow stable operation with higher premixed gasoline ratio without impacting COV of IMEP or HC/CO emissions

- For fixed diesel SOI timing, biodiesel blends advanced combustion phasing
  - Differences in NTC region heat release and duration
  - Allows higher ratio of gasoline
  - Allows increased stability for high levels of ethanol

- Have examined gasoline with ULSD, B5 and B20 Blends
  - SME with Cetane number of 47.50
  - ULSD with Cetane number of 42.5 and 46.5
  - UTG – 96 with RON of 97.2

Diesel SOI = 60 CA bTDC

Noise Limited Combustion Phasing

Biodiesel blends allow combustion phasing to be maintained despite increasing amount of gasoline while observing MPRR limit of 100kPa/deg
Ethanol Blends Allow for RCCI Load Expansion

- DI to PFI fueling ratio changes
  - Lower reactivity of E85 requires higher fraction of diesel / biodiesel
  - Both a chemical octane effect and a charge cooling effect with E85

- Cyclic instabilities observed at high load limit for E85
  - High pressure rise followed by near misfire
  - Minor stochastic perturbations may cause large operational changes due to homogeneity of fuel

![Graph showing ethanol blends require higher percentage of diesel fuel](image1)

- At fixed diesel SOI, ethanol blends retard combustion phasing

- 2000 RPM, 7.0 bar BMEP
  - Diesel SOI = 60 CA bTDC
  - CA50 (DA TDC) = 436 kPa/deg
  - 1000 kPa/deg

- 3000 rev/min
  - 45 BTE (%)
  - 30 RCCI (E20/diesel)
  - 40 RCCI (gas/diesel)
  - 5 CDC (diesel)
Current RCCI Operation Includes Most of LD Drive Cycles

- RCCI mapped with focus on efficiency and lowest possible emissions
  - Peak BTE within light-duty drive cycle range (> peak BTE of 1.9L GM diesel)
- Current RCCI map requires mode-switching to cover light-duty drive cycles
  - 100% coverage of low temperature combustion is necessary to avoid mode-switching

RCCI Map overlain on diesel map

**Features**

- **UDDS**: Urban Dynamometer Driving Cycle
  - Commonly called the "LA4" or "the city test" and represents city driving conditions

- **HWFET**: Highway Fuel Economy Test
  - Represents highway driving conditions under 60 mph

- **US 06**: High acceleration aggressive driving schedule – also called the "Supplemental FTP"

- **NYCC**: New York City Cycle
  - Features low speed stop-and-go traffic conditions
Range of Compression Ignition Strategies Includes LTC and HTC

Diesel HCCI

Dual Fuel RCCI

PCCI

CDC

HCCI

PFS

Majority Premixed PPC

Majority Stratified PPC

GCI LTC/HTC

Level of In-Cylinder Fuel Stratification at the Start of Combustion
Matching Engine Based on 0-60 Performance

- Current range of engine maps allows matching based on performance to have best comparison against “representative” 2009 PFI baseline
  - FY 12 Milestone compared modeling results to 4.0L only
  - Specifically asked to be addressed by ACEC and in AMR reviewer notes

- 0-60 mph acceleration simulations performed with standard performance transmission (non-fuel economy optimized transmission) for each vehicle on same mid-size sedan

- 2.7 L PFI engine best match for performance (2.4 L best fuel economy)
  - 1.8 L PFI underpowered for vehicle size

<table>
<thead>
<tr>
<th>Engine</th>
<th>Distance(M)</th>
<th>Time(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDC</td>
<td>154.0</td>
<td>9.50</td>
</tr>
<tr>
<td>CDC/RCCI</td>
<td>154.1</td>
<td>9.50</td>
</tr>
<tr>
<td>PFI4.0</td>
<td>124.5</td>
<td>7.90</td>
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<td>PFI2.7</td>
<td>155.0</td>
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<td>10.90</td>
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<tr>
<td>PFI1.8</td>
<td>234.7</td>
<td>15.20</td>
</tr>
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Simulated time for 0-60 mph acceleration
Corollary Study: Aftertreatment Integration with RCCI

- Drive cycle simulations help illustrate challenges
  - Estimate emissions and exhaust temperatures over drive cycles

Modeled engine out emissions reductions compared to Diesel

<table>
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<th>Reductions With RCCI</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
</tr>
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<tbody>
<tr>
<td>UDDS*</td>
<td>17%</td>
<td>+ 240%</td>
<td>+ 150%</td>
</tr>
<tr>
<td>HWFET</td>
<td>21%</td>
<td>+ 300%</td>
<td>+ 140%</td>
</tr>
<tr>
<td>US06</td>
<td>8%</td>
<td>+ 310%</td>
<td>+ 140%</td>
</tr>
<tr>
<td>NY City</td>
<td>+4%</td>
<td>+ 220%</td>
<td>+ 150%</td>
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Modeled CDC and RCCI-Mixed-Mode Exhaust Temps over UDDS

- Examples 1500 RPM, 5.5bar and 2.0bar BMEP [Model DOC (1.25 L, 100g/Ft^3 Pt, 400 csi)]

Experimental Data Showing Challenges with Low Temperature Aftertreatment

1500rpm, 5.5bar BMEP (280°C)

1500rpm, 2.0bar BMEP (180°C)
Corollary Study: Aftertreatment Integration with RCCI

- Drive cycle simulations help illustrate challenges
  - Estimate emissions and exhaust temperatures over drive cycles

**B20 Map Modeled engine out emissions reductions compared to Diesel**

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<td>+ 150%</td>
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**E30 Map Modeled engine out emissions reductions compared to Diesel**

<table>
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<th>HC%</th>
<th>CO%</th>
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</thead>
<tbody>
<tr>
<td>UDDS</td>
<td>16.0%</td>
<td>+195.0%</td>
<td>+82.5%</td>
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<td>HWFET</td>
<td>18.6%</td>
<td>+452.7%</td>
<td>+141.0%</td>
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<tr>
<td>US06</td>
<td>9.5%</td>
<td>+264.2%</td>
<td>+89.1%</td>
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<tr>
<td>SC03</td>
<td>10.7%</td>
<td>+178.3%</td>
<td>+78.6%</td>
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</table>