Maximizing Engine Efficiency by Controlling Fuel Reactivity Using Conventional and Alternative Fuels

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Acknowledgments

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Outline

- Motivation for investigating internal combustion (IC) engine efficiency
- Requirements for high-efficiency combustion
- A pathway to high-efficiency clean combustion using in-cylinder blending of fuels with different auto-ignition characteristics
  - Conventional fuels
  - Details of combustion process
  - Alternative fuels
- Conclusions

Why research IC engine efficiency?

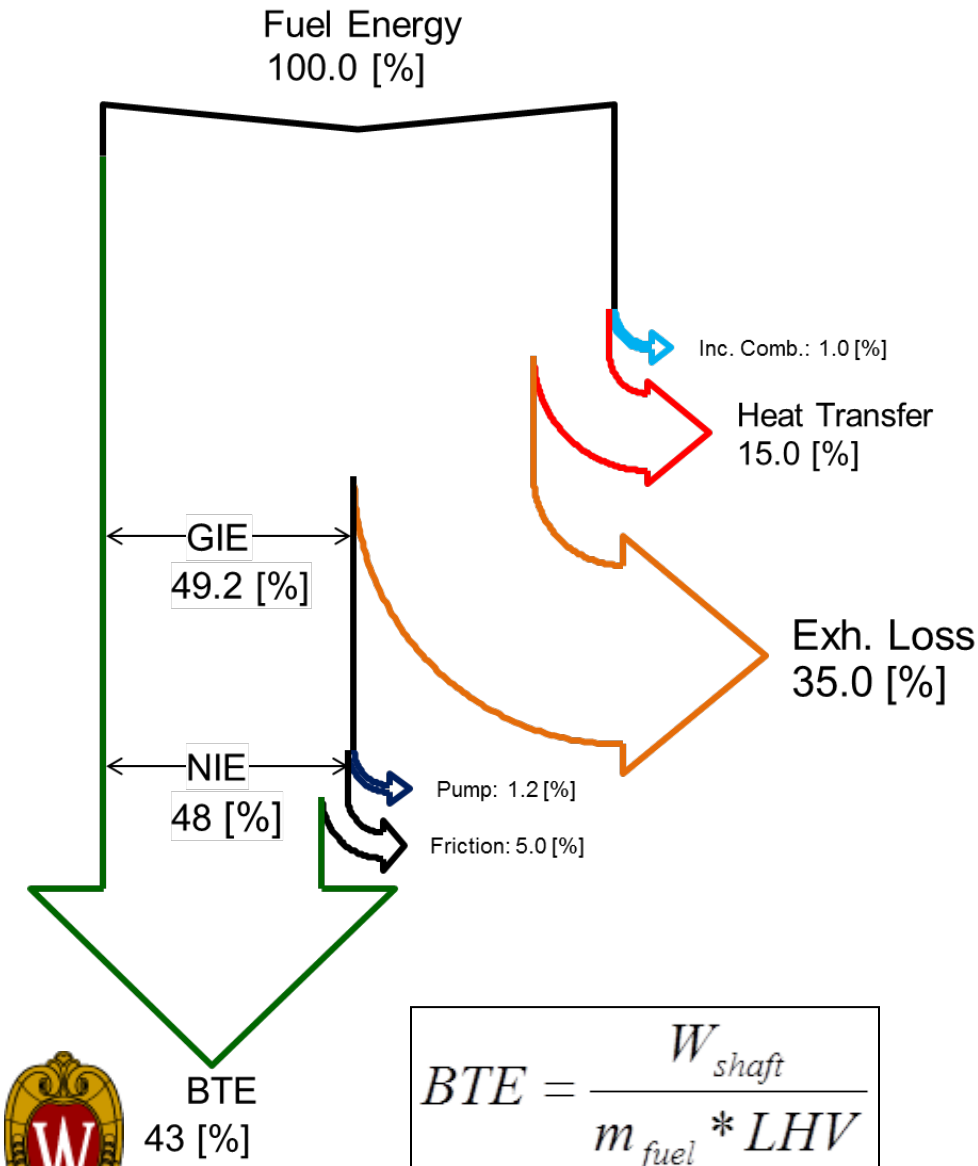
- Internal combustion engines are used in a variety of applications from transportation to power generation
- 70% of all crude oil consumed is used to fuel internal combustion engines
  - United States spends more than 3% of GDP on oil to fuel IC engines
- IC engines are expected to be the dominant (>90%) prime mover for transportation applications well into the future (projections through 2050)[1,2,3]
- Improvements in the efficiency of IC engines can have a major impact on fossil fuel consumption and green house gas (GHG) emissions on a global scale
  - A 1% improvement in efficiency equates to a fuel savings of ~$4 billion per year

[1] Quadrennial Technology Review, DOE 2011

[2] *Review of the Research Program of the FreedomCAR and Fuel Partnership: 3rd Report*, NRC 2010

[3] Energy Information Agency, *Annual Energy Outlook 2012*, June 2012.

Maximizing Engine Efficiency



$$BTE = \frac{W_{shaft}}{m_{fuel} * LHV}$$

- Fuel energy is wasted due to:
  - Incomplete combustion (i.e., combustible material flowing out the exhaust)
  - Heat transfer losses to the coolant, oil, and air
  - Unrecovered exhaust energy
  - Pumping losses
  - Friction losses
- Research goal is to maximize the BTE by developing a fundamental understanding of pathways leading to high efficiency energy conversion and proposing techniques to achieve this goal

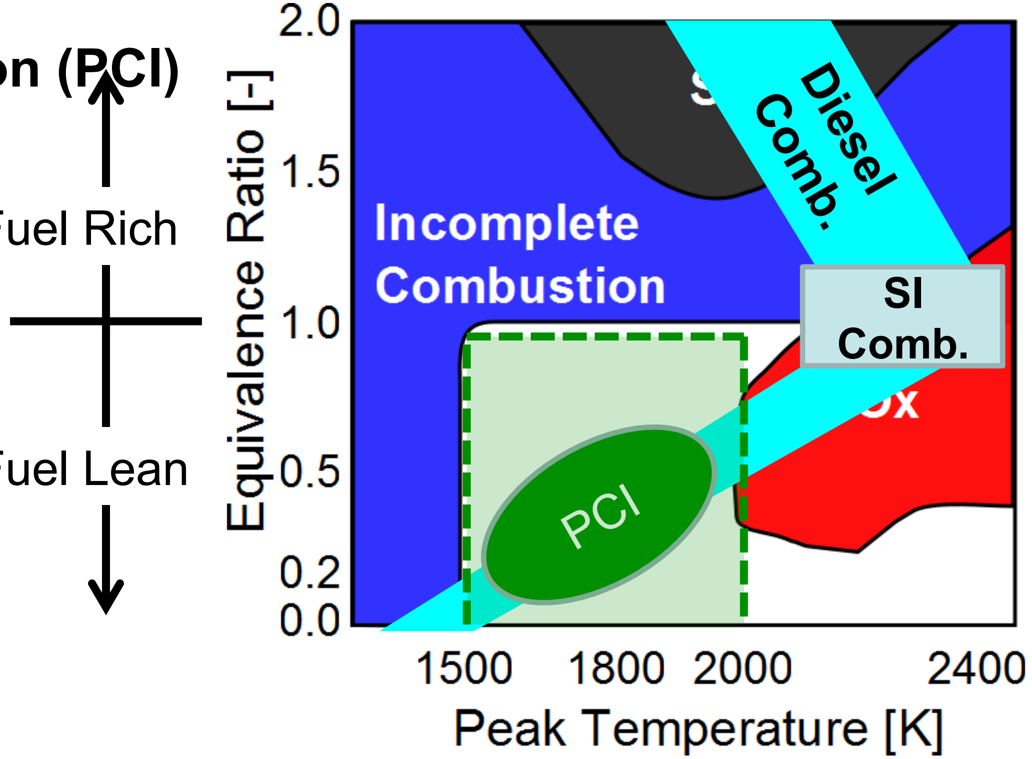
Advanced Combustion Modes

- Ideal combustion system has a high compression ratio using a lean, well-mixed charge, resulting in a short burn duration near TDC with temperatures between 1500 K and 2000 K

- Fuel and air are well mixed (like SI comb.)
- Compression ignition (like diesel comb.)
- Combustion controlled by chemistry (comb. Control is a challenge)

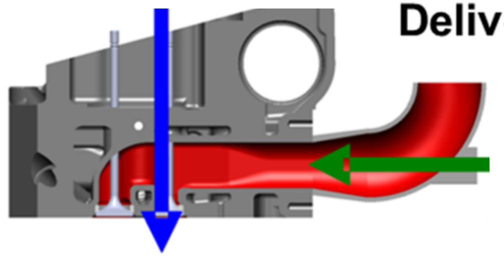
Premixed Compression Ignition (PCI)

- With the correct selection of conditions, PCI combustion have all the traits of the ideal combustion system
  - Lean well mixed charge
  - Short burn duration
  - High compression ratio



Advanced Combustion Modes

- Highly-premixed compression ignition (PCI) strategies offer attractive emissions and performance characteristics; however, in practice PCI strategies are generally confined to low-load operation due to
  - lack of adequate combustion phasing control
  - difficulties controlling the rate-of-heat release (combustion noise)
- Common fuels (e.g., gasoline and diesel fuel) have different auto-ignition characteristics
  - Diesel fuel is easy to ignite (high reactivity) – good for low load/low temp.
  - Gasoline is difficult to ignite (low reactivity) – good for high load/high temp
- This work proposes in-cylinder fuel blending of two fuels with different auto-ignition characteristics to simultaneously control combustion phasing and rate-of-heat release
- Alternative combustion mode controlled by fuel reactivity → **Reactivity Controlled Compression Ignition (RCCI) combustion**



High Reactivity Fuel (Diesel fuel, bio-diesel, DME, etc..)

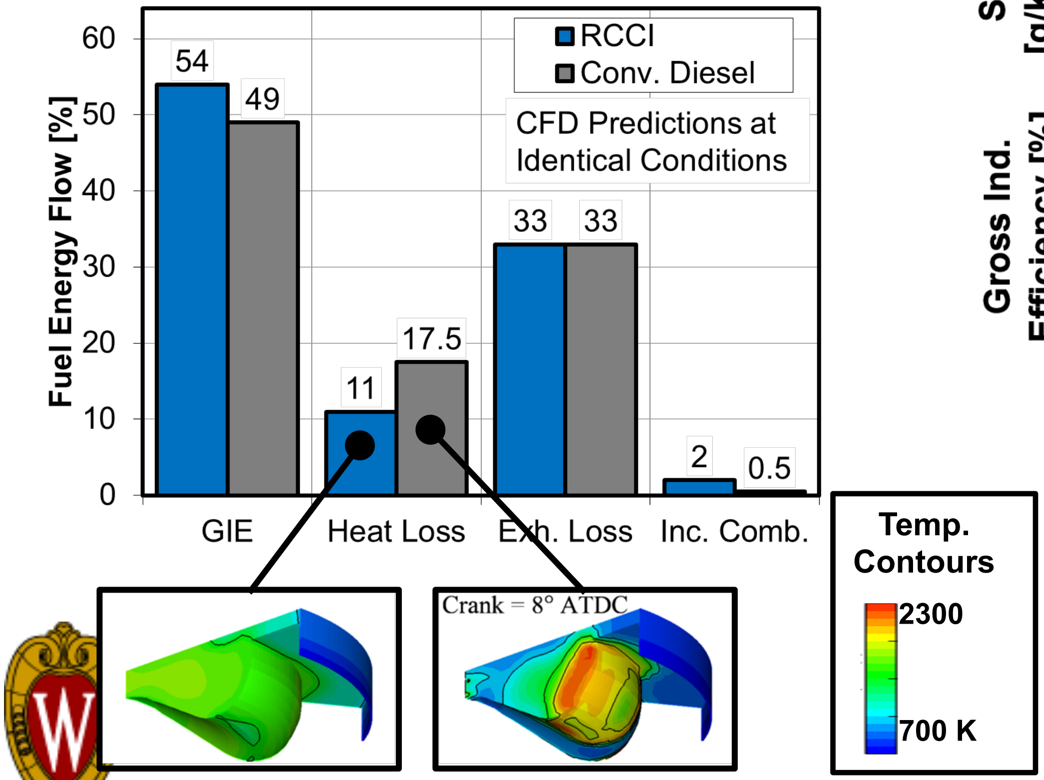
Fuel Delivery Strategy

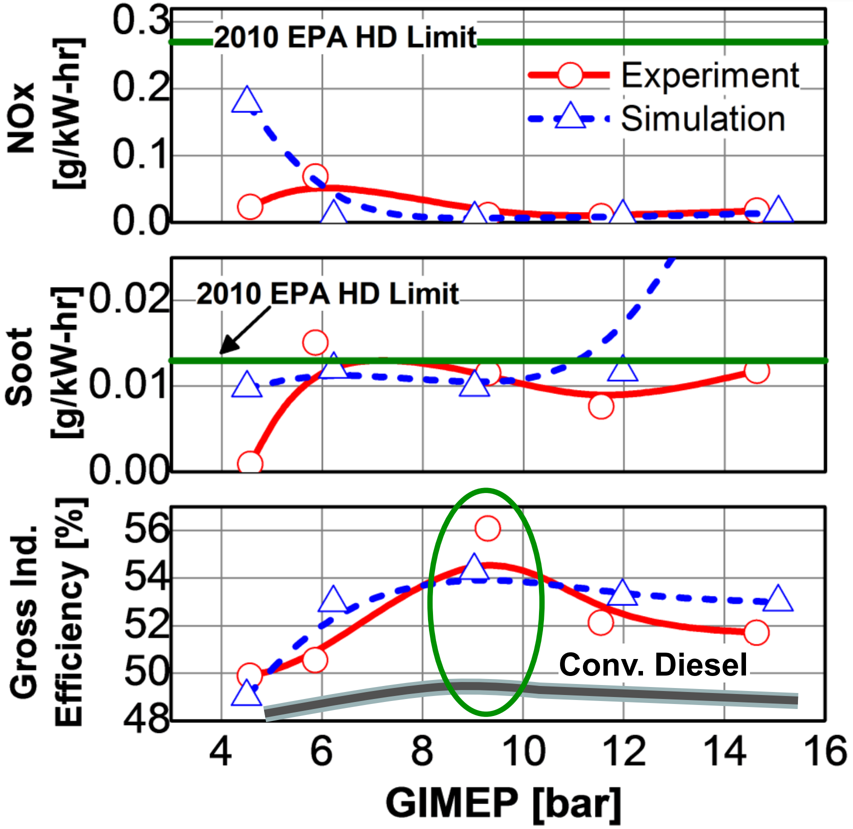
Low Reactivity Fuel (Gasoline, ethanol, natural gas etc…)

Demonstration of RCCI Performance

Kokjohn et al. IJER 2011
Hanson et al. SAE 2010-01-0864

- Heavy-duty RCCI has demonstrated near zero NOx and soot and a **peak gross indicated efficiency of 56%**
- Conventional diesel shows 49% GIE at identical conditions with an order of magnitude higher NOx and soot

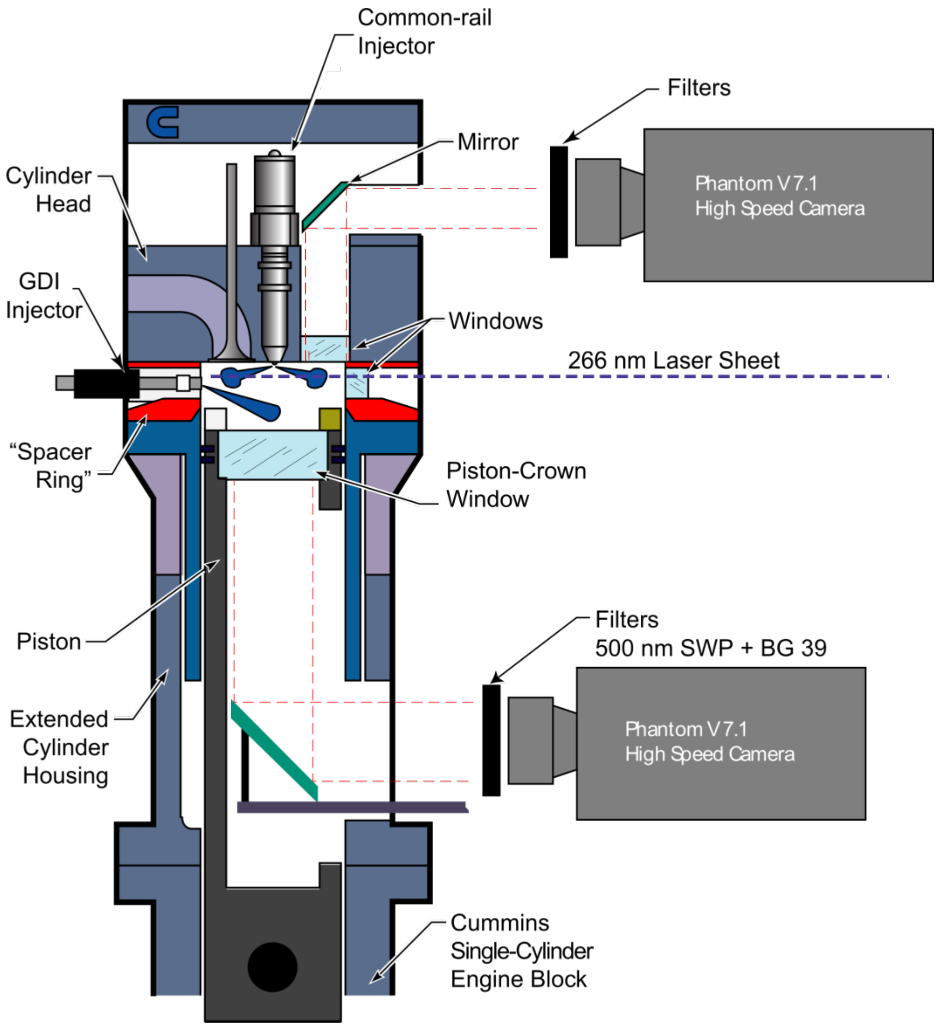




- GIE improvement is primarily explained by reduced heat transfer
  - Lower temperatures by avoiding near stoichiometric regions
  - High temperature regions are away from surfaces

What are the dominant mechanisms controlling RCCI combustion?

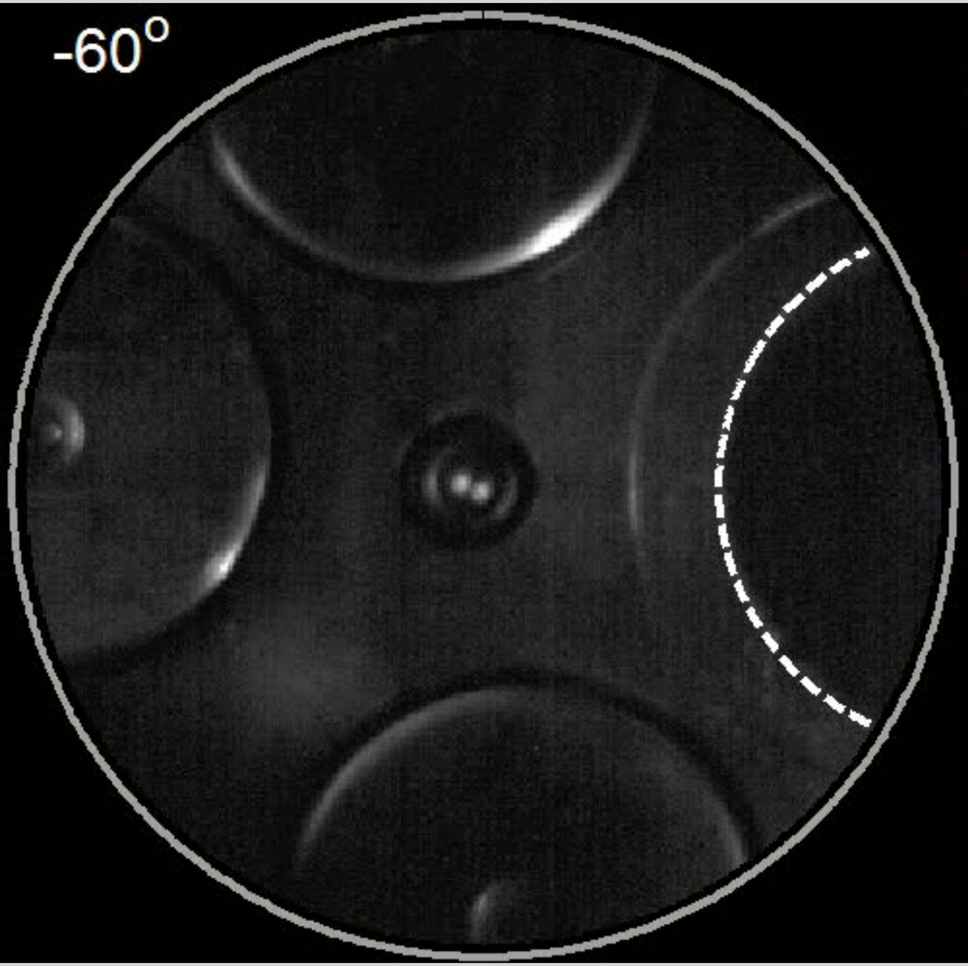
- Answer this question using optical engine experiments.
- Optical engine has several windows allowing imaging of the spray, mixing, and combustion process
- High speed chemiluminescence imaging
  - Evaluate overall reaction zone growth
- Fuel tracer fluorescence imaging
  - Relate the fuel distribution prior to ignition to the reaction zone progression
  - Evaluate heat release rate control using spatial stratification of fuel reactivity

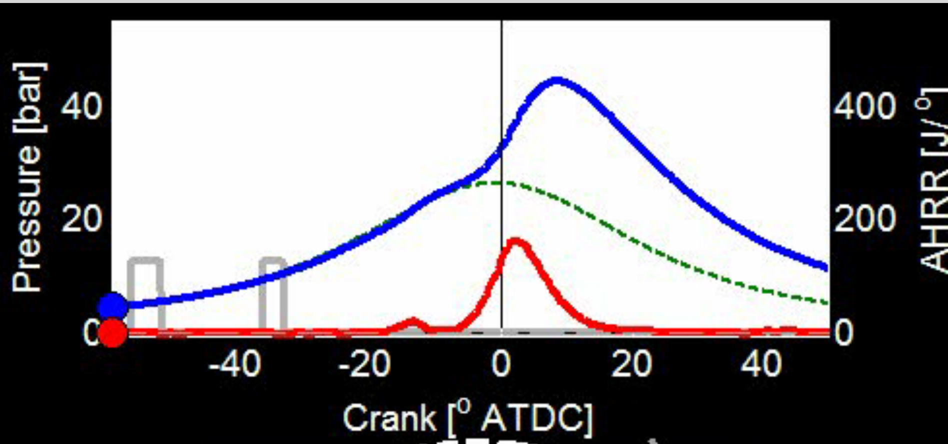


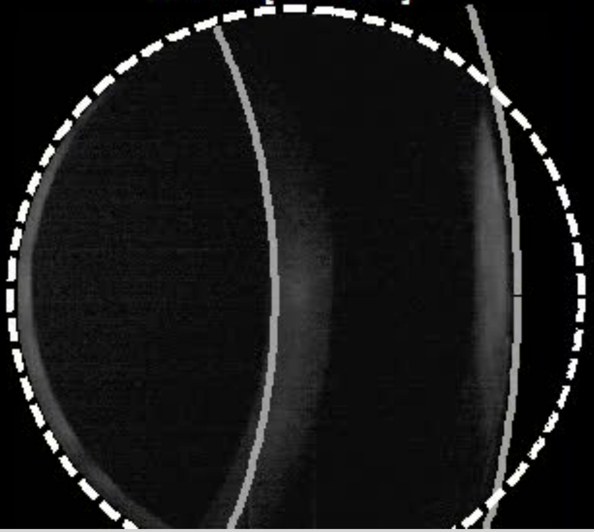
High Speed Combustion Luminosity Imaging

Load: 4.2 bar IMEP
Speed: 1200 rpm
Intake Temperature: 90° C
Intake Pressure: 1.1 bar abs.

GDI SOI: -240°ATDC
n-heptane SOI: -57°/-37° ATDC
Iso-octane mass %: 64
Effective gain: 500







Bowl Window

Cylinder Head Window

Kokjohn et al. ILASS 2011

Toluene Fuel Tracer PLIF

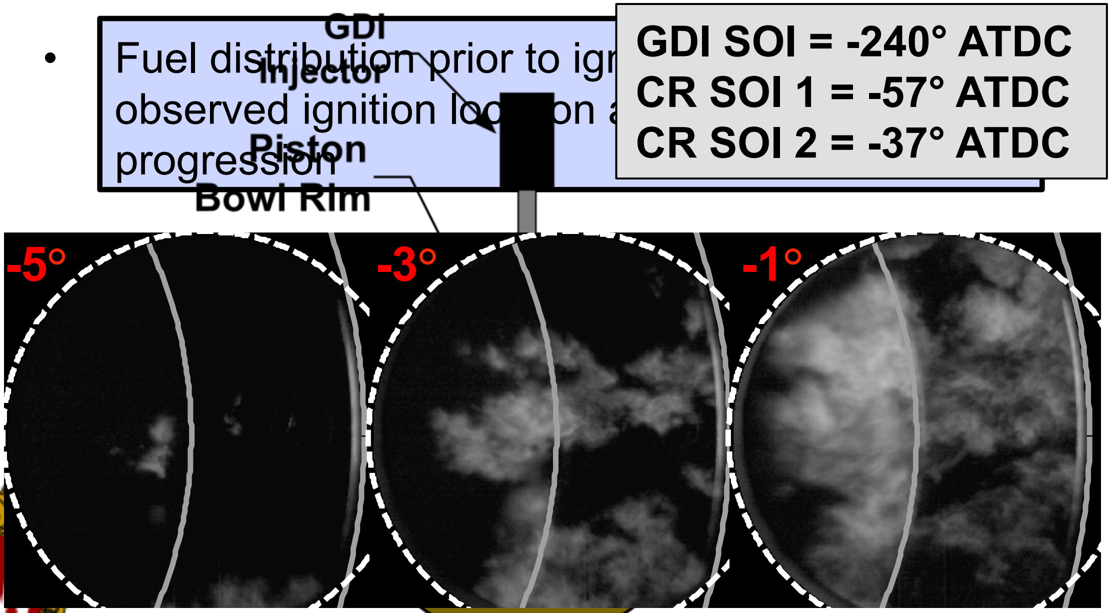
- In-cylinder fuel distribution measurements using fuel tracer fluorescence imaging
- Image shortly before low-temperature heat release shows a stratified local octane # (PRF) distribution resulting from the direct-injection event
- Most reactive region (minimum octane #) is located near the center of the piston bowl rim
- Reactivity decreases (octane # increases) toward the center of the combustion chamber

Diagnostic Overview

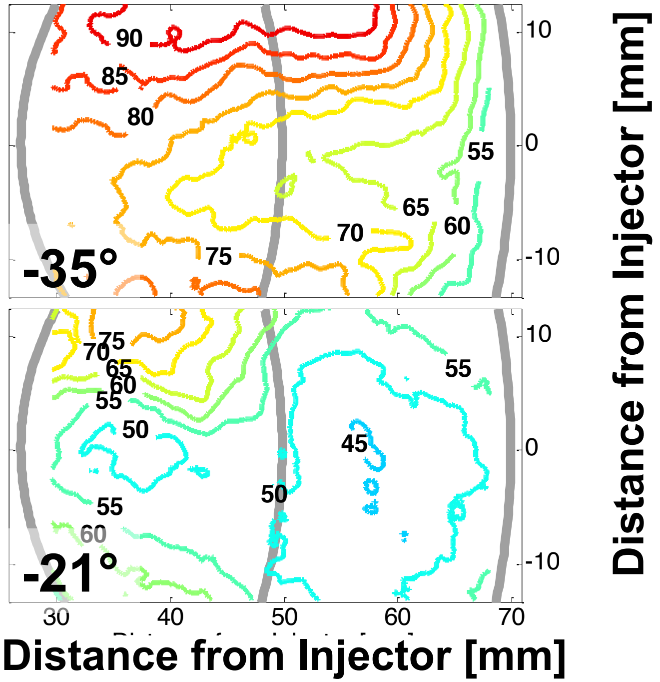
1. Fuels doped with 1% toluene
2. Toluene fluorescence excited by 266 nm (UV) laser sheet
3. Fluorescence images processed to show fuel distribution

- Fuel distribution prior to ign observed ignition lo on a progression

GDI SOI = -240° ATDC
CR SOI 1 = -57° ATDC
CR SOI 2 = -37° ATDC



Local Octane # (PRF) Distribution



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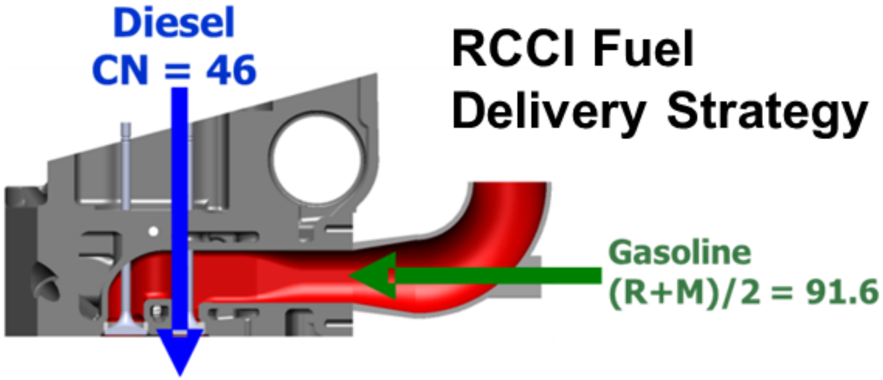
RCCI Combustion Summary

- Combustion phasing is controlled by the overall fuel blend (i.e., ratio of gasoline-to-diesel fuel – or fuel reactivity)

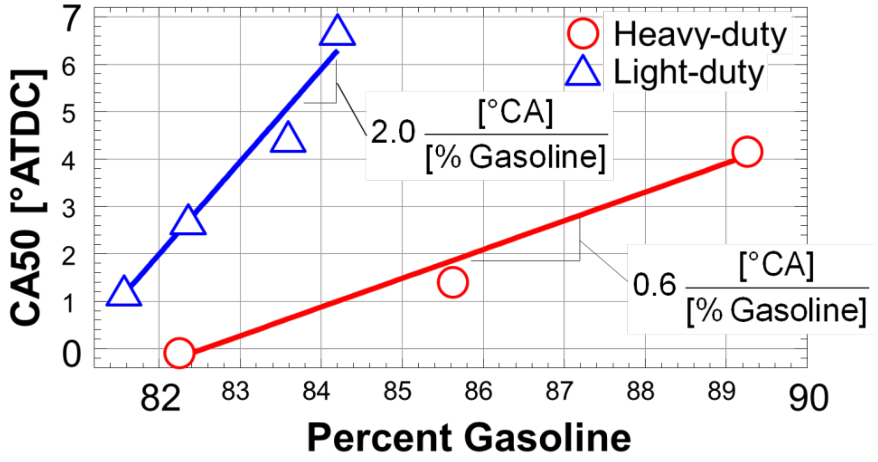
RCCI Fuel Delivery Strategy

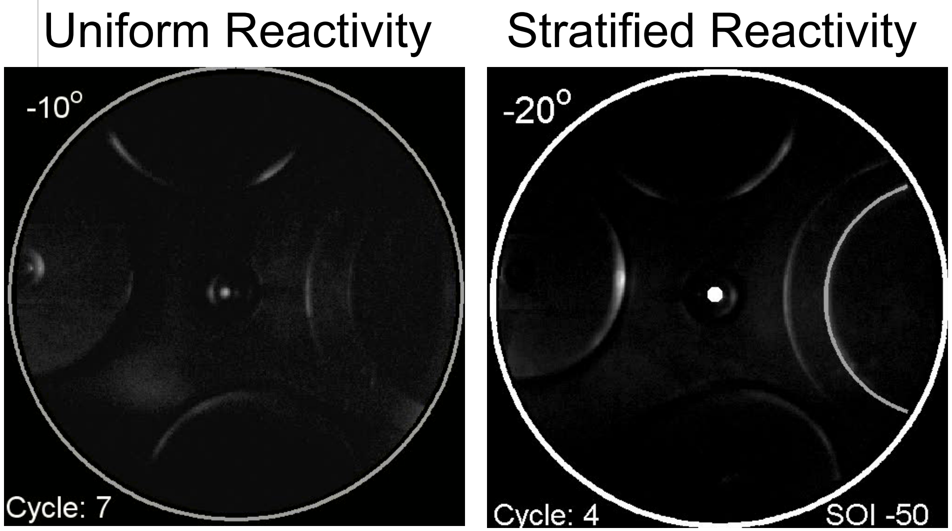


- The combustion duration is controlled by spatial stratification in the fuel reactivity

- **RCCI combustion address the two primary issues of PCI combustion**

Kokjohn et al. SAE 2011-01-0357



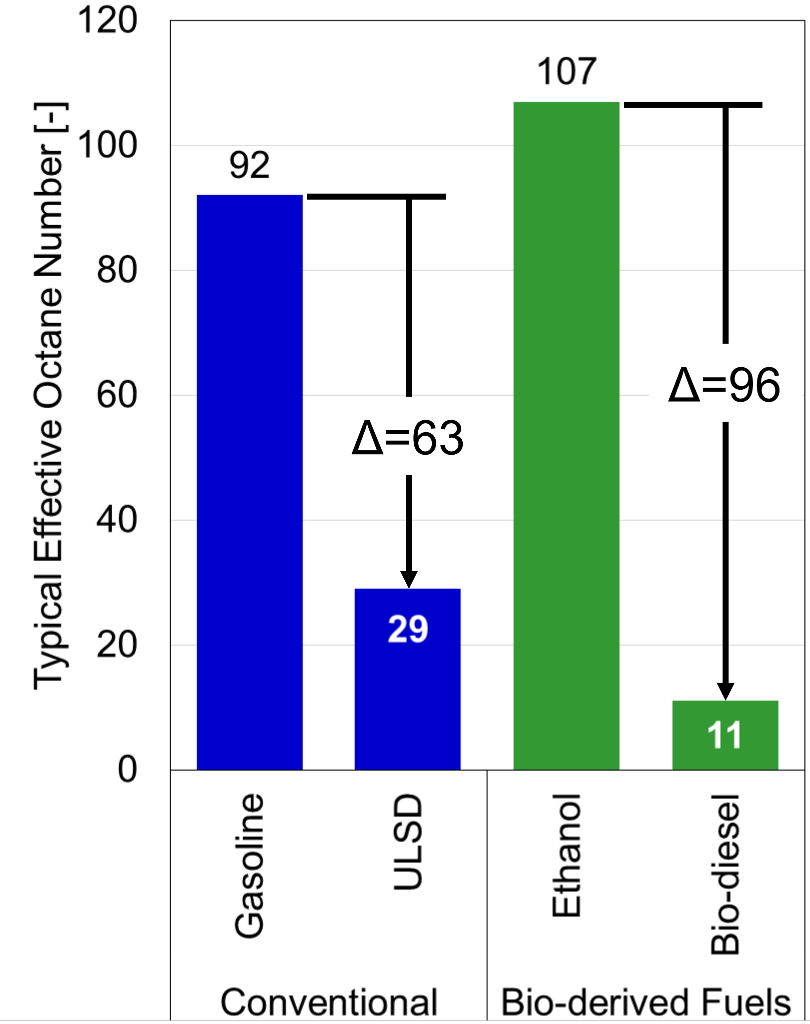

Uniform Reactivity
Stratified Reactivity

Kokjohn et al. SAE Int. J. of Engines 2012

Can bio-derived fuels be used for RCCI?

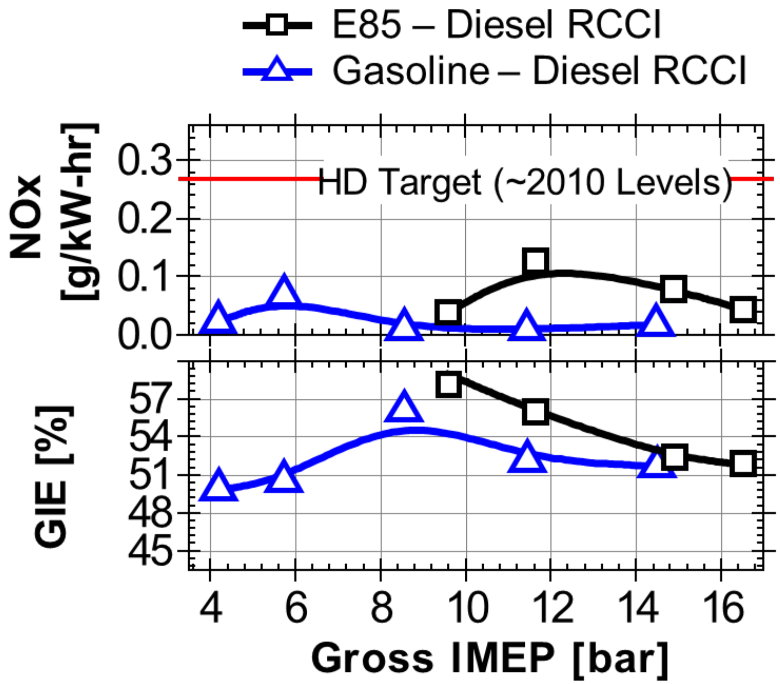
- RCCI depends on auto-ignition characteristics of the charge → controlled by in-cylinder blending
- RCCI is inherently fuel flexible (with two fuels with different auto-ignition characteristics)

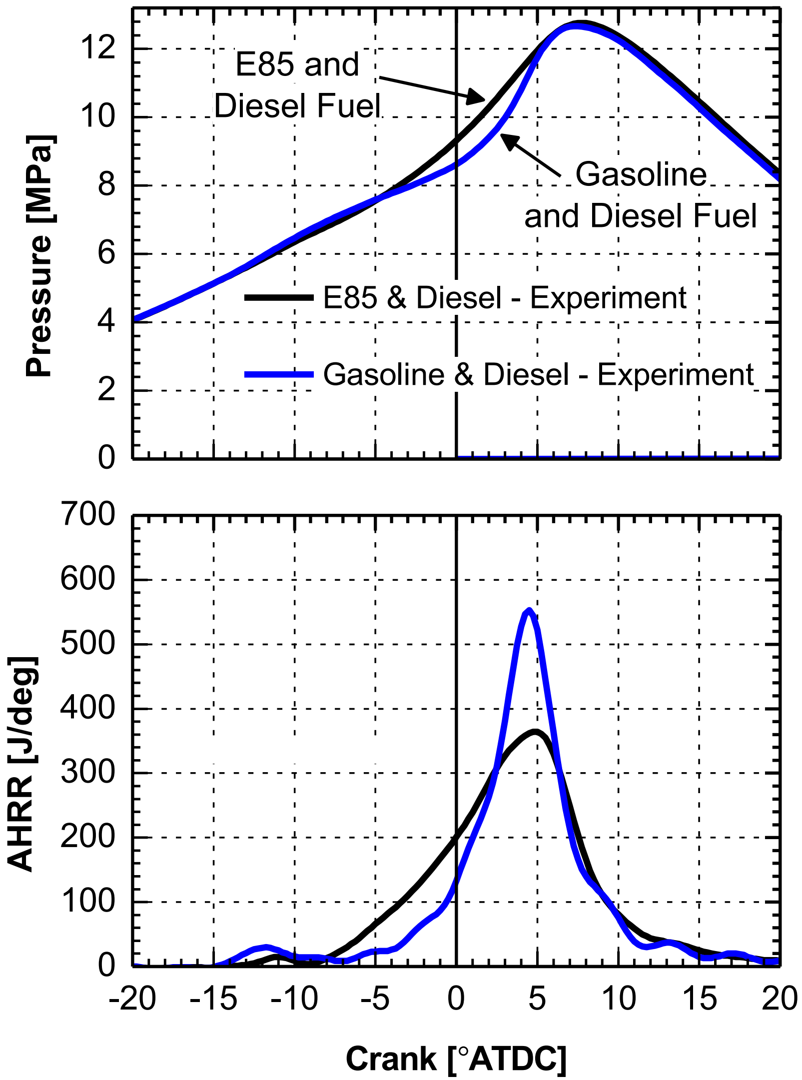
- Example, ethanol is less reactive than gasoline and bio-diesel is (typically) more reactive than diesel fuel → larger differences in auto-ignition characteristics → great fuels for RCCI combustion!



Can bio-derived fuels be used for RCCI?

- Gasoline-diesel RCCI is compared to E85-diesel RCCI combustion
- E85-diesel DF RCCI exhibits significantly reduced HRR compared to gasoline-diesel RCCI → quieter operation and extended load range
- Both show near zero levels of NOx and GIE significantly above state of the art diesel engines (diesel GIE ~49% at peak)

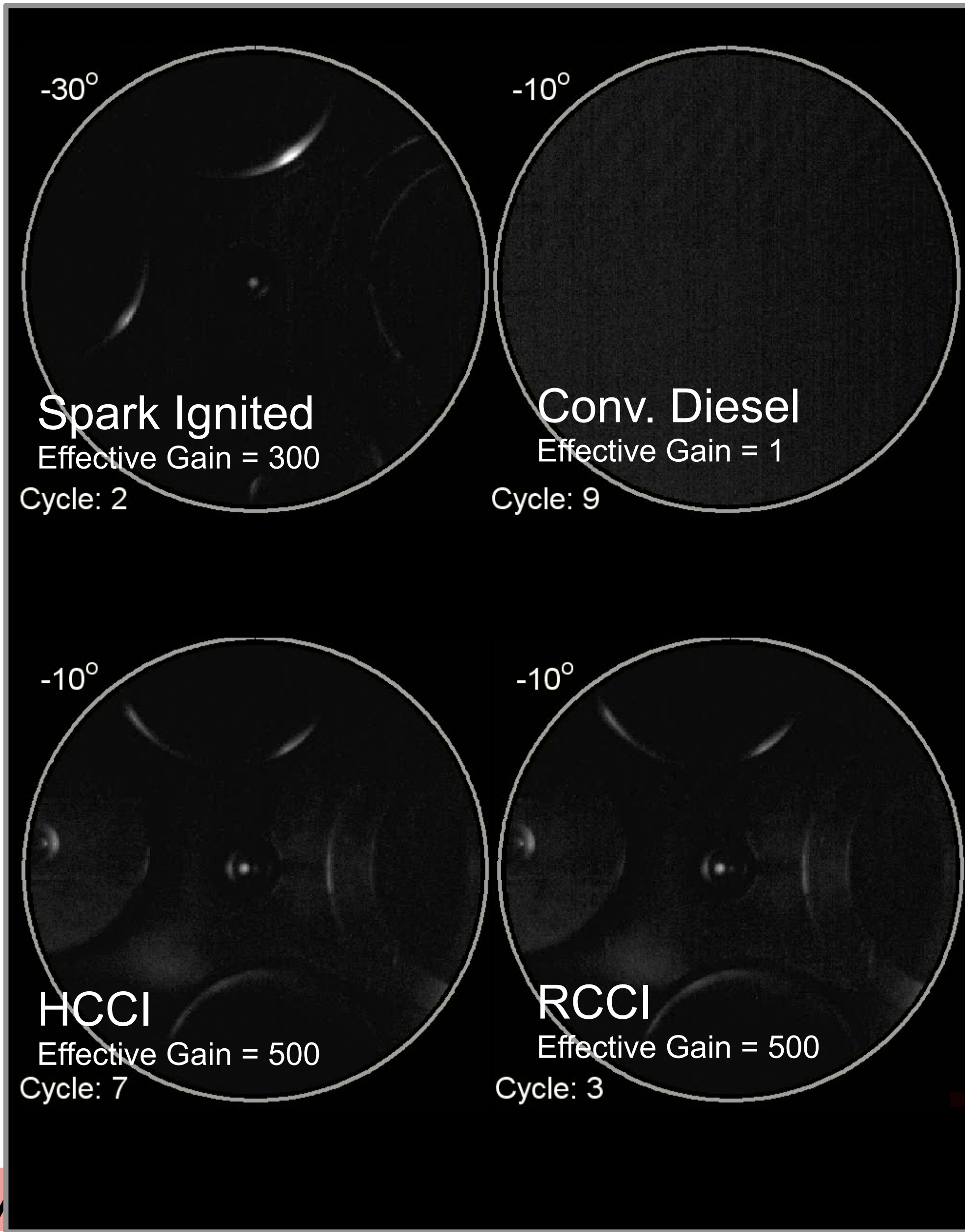




Conclusions

- A dual fuel PCI concept is proposed using in-cylinder blending of two fuels with different auto-ignition characteristics
- Controlled PCI operation demonstrated with very high efficiency and near zero NOx and soot emissions over a range of loads
- New combustion concept addresses the two primary issues limiting acceptance of PCI combustion
  - Combustion phasing is easily controlled by adjusting the overall fuel reactivity (e.g., gasoline-to-diesel ratio)
  - Combustion duration is controlled by introducing spatial stratification into the auto-ignition characteristics of the charge
- RCCI combustion is inherently fuel flexible and well-suited for use with bio-derived fuels → engine adapts to fuel ignition characteristics on-the-fly to maintain peak efficiency

Questions?


-30°
Spark Ignited
Effective Gain = 300
Cycle: 2
-10°
Conv. Diesel
Effective Gain = 1
Cycle: 9
-10°
HCCI
Effective Gain = 500
Cycle: 7
-10°
RCCI
Effective Gain = 500
Cycle: 3