Fuel Effects on Advanced Combustion: Heavy-Duty Optical-Engine Research

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Overview

Timeline

- Project provides fundamental research to support DOE/ industry fuel-technologies projects
- Project directions and continuation are evaluated annually

Budget

- Project funded by DOE/VT:

  FY08 – $670K

  FY09 – $600K

Barriers*

- "Lesser-known combustion and emission-formation characteristics of non-petroleum-based fuels"
- "Lack of adequate combustion understanding and simulation capability, especially for new combustion regimes"
- "Need better understanding of composition range of fuels and impacts on advanced combustion"

* Source: *21st Century Truck Partnership Roadmap*

Partners

- Project lead: Sandia – C.J. Mueller (PI) B.T. Fisher (post-doc), A.S. Cheng (visitor)
- 15 industry partners in Advanced Engine Combustion Working Group
- Coordinating Research Council (CRC)
- Caterpillar Inc.

Objectives

Develop the fuel-effects and engine-combustion science-base required for maximum petroleum displacement

- Specific objectives of work since FY08 Annual Merit Review
  - Identify underlying cause(s) of NO_x increase when fueling with biodiesel
  - Study effects of fuel volatility on CI engine efficiency and emissions when using an early direct-injection strategy
  - Establish capability to measure in-cylinder liquid-phase fuel penetration under early direct-injection operating conditions
  - Contribute to development of surrogate diesel fuels for use in combustion modeling studies

Milestones

- ✓ **September 2008**
  Demonstrate capability to make in-cylinder liquid-phase fuel penetration measurements under early direct-injection conditions with single-component, low-cetane fuel
- ✓ **March 2009**
  Complete publication summarizing origins of biodiesel NO_x increase
- **August 2009**
  Complete publication summarizing fuel-volatility effects on efficiency and emissions under early direct-injection conditions
- **September 2009**
  Complete publication summarizing in-cylinder liquid-phase fuel penetration results for two single-component, low-cetane fuels
- **October 2009**
  Co-lead AVFL-18 team to formulate a surrogate for #2 diesel that has been validated to match certain desired fuel properties

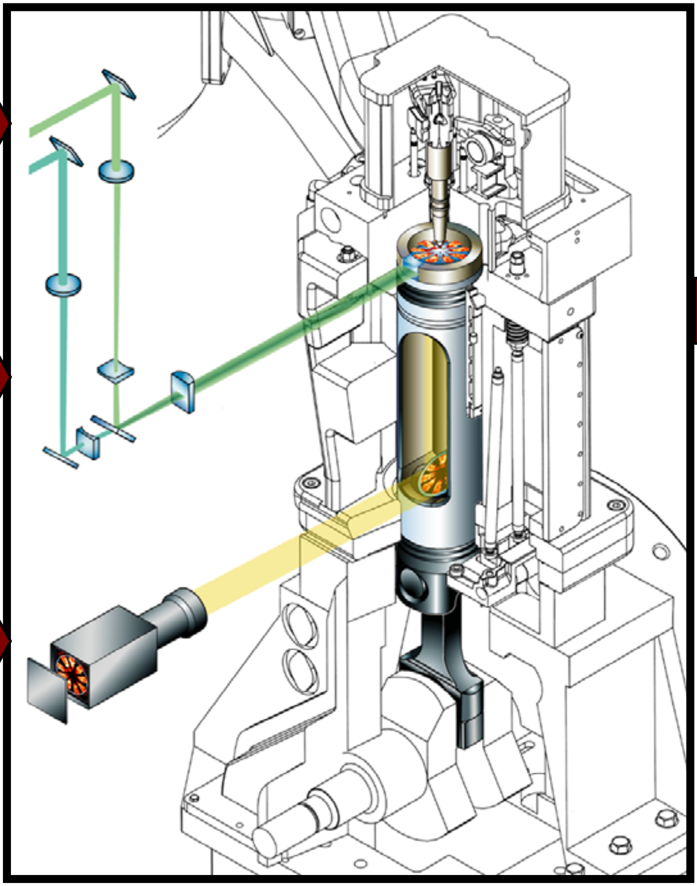
Approach

Use optical engine and advanced diagnostics to understand fuel effects on in-cylinder processes

Modern Engine Hardware

Advanced Fuels

Guidance from Industry, Academia, Nat'l Labs



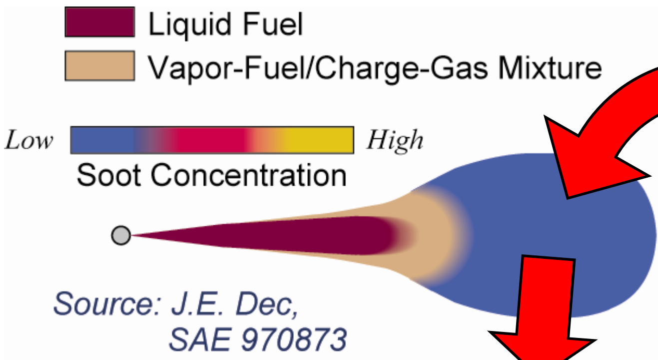
Science-Base to Increase Efficiency and Reduce Emissions

Technical Accomplishments

- Identified mechanisms explaining NO_x increase when fueling with biodiesel
- Showed how increasing diesel-fuel volatility can dramatically increase efficiency and decrease emissions under early direct-injection operating conditions
- Established capability to quantitatively measure in-cylinder liquid-phase fuel penetration under early direct-injection operating conditions
- Helped form and lead working group to develop surrogate diesel fuels for use in combustion modeling studies

Technical Question #1: What Causes the Biodiesel NO_x Increase? (1 of 2)

- **Reacting mixtures closer to stoichiometric during ignition**



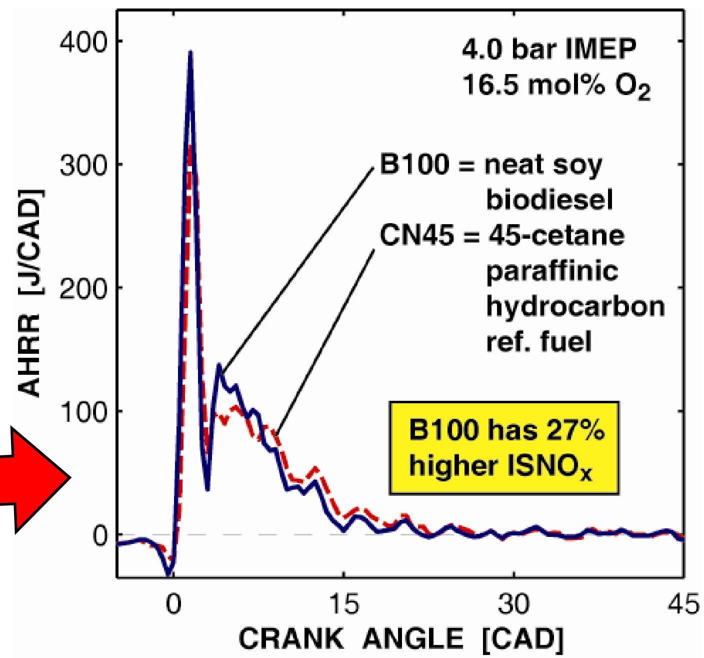
$$\phi = \frac{\left(m_A / m_F \right)_{st}}{\left(\dot{m}_A / \dot{m}_F \right)} > 1$$

smaller for biodiesel (fuel contains oxygen) (numerator)

approx. constant regardless of fuel (denominator)

– Higher temperatures, faster reaction rates, less subsequent mixing-controlled combustion required for complete oxidation, shorter combustion duration, longer residence time at high temperature

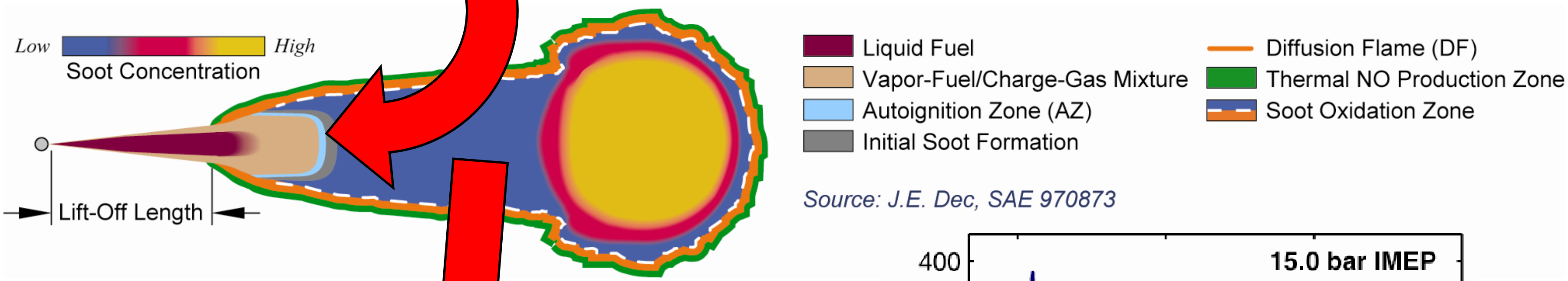
– Consistent with biodiesel NO_x increase at lower loads



See SAE 2009-01-1792 for details

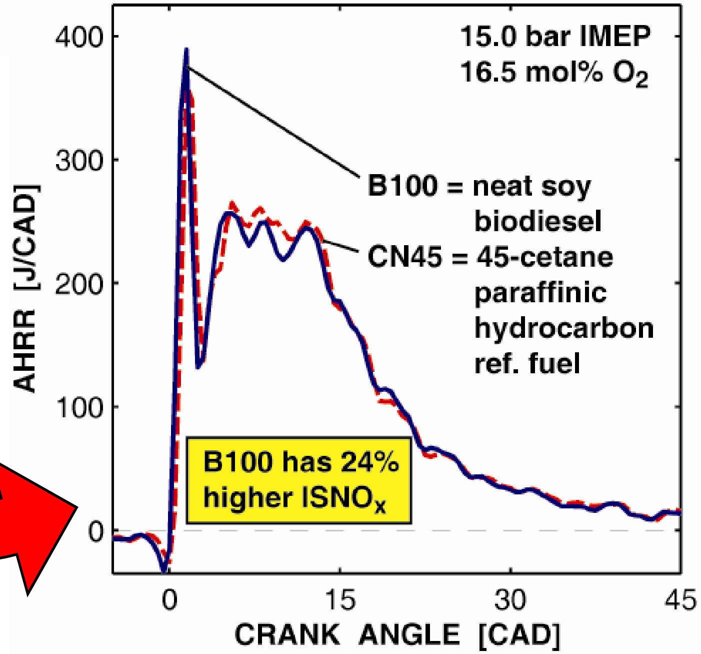
Technical Question #1: What Causes the Biodiesel NO_x Increase? (2 of 2)

- **Reacting mixtures closer to stoichiometric in the standing premixed autoignition zone (AZ) near the lift-off length**



Source: J.E. Dec, SAE 970873

  - Effects similar to those at ignition, plus less soot → less radiative heat loss → higher temperatures
  - Consistent with biodiesel NO_x increase at higher loads



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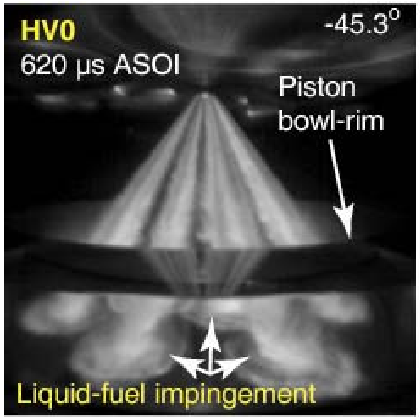
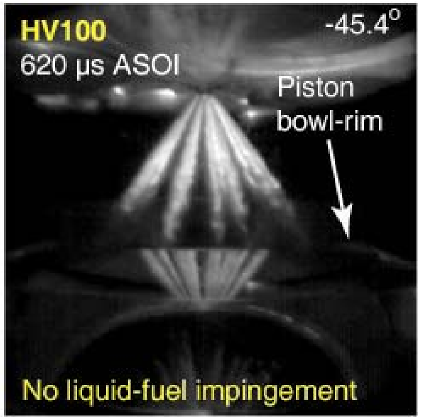
Technical Question #2: Does Increasing Fuel Volatility Benefit Early-DI Operation?

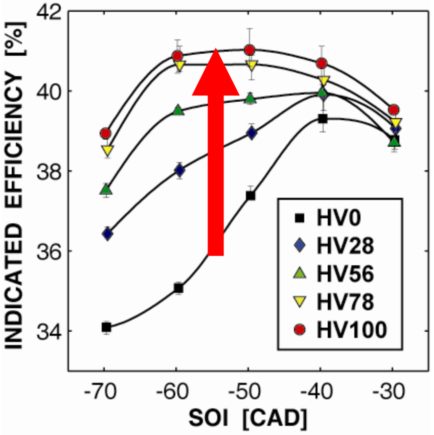
- **Yes. Avoiding fuel-film formation enables significantly higher efficiency with lower emissions.**

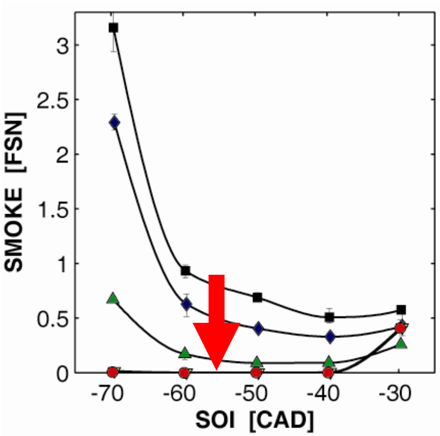
HVx = x vol% high-volatility fuel blended with #2 ULSD

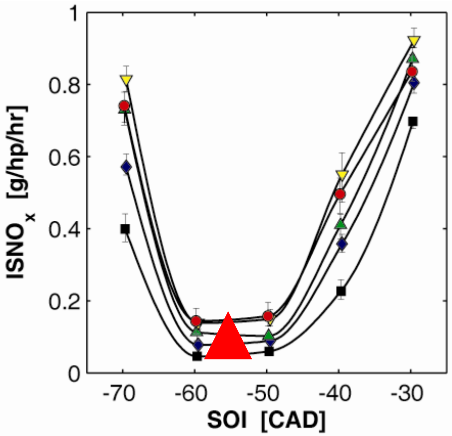
SOI = start of injection

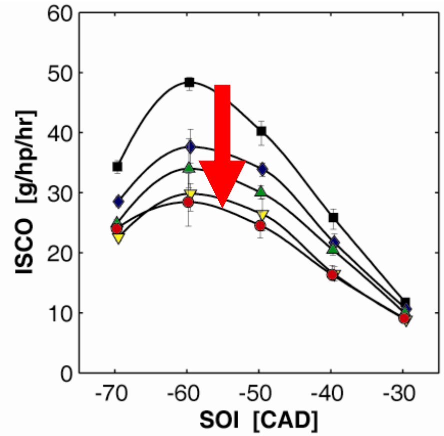


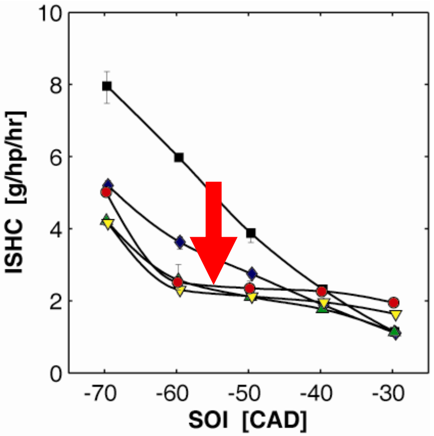




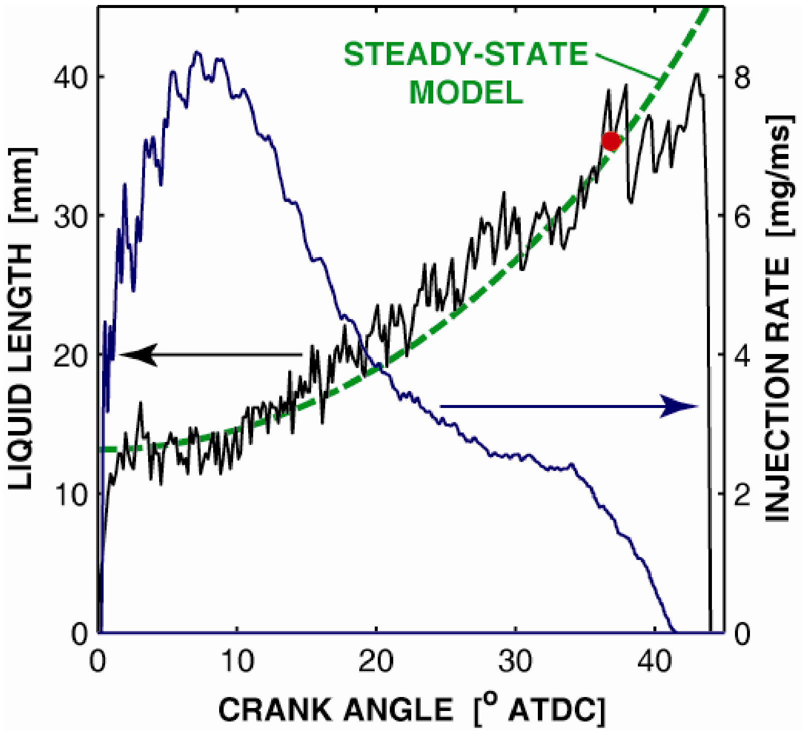


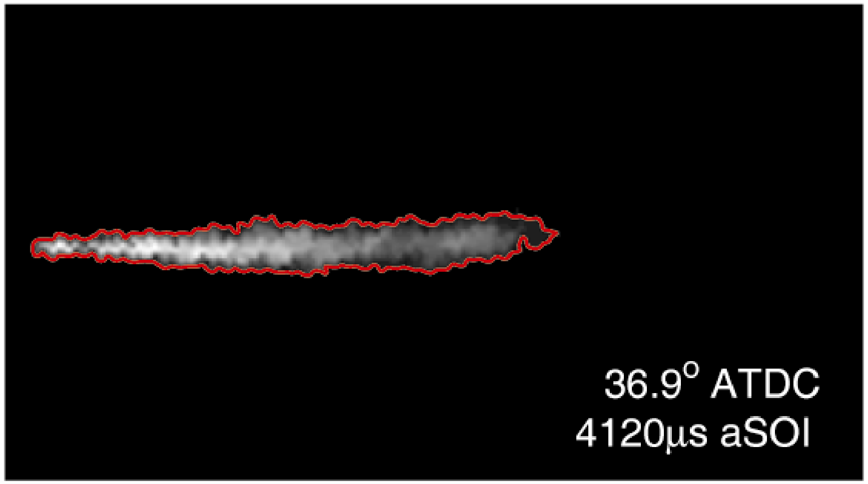






Tech. Question #3: How Does Liquid Length Vary under Unsteady In-Cylinder Conditions?





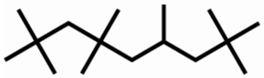
In-cylinder elastic-scattering image of liquid-phase fuel

- **Good agreement with steady-state model** (D.L. Siebers, SAE 1999-01-0528)
  - Strong dependence on instantaneous density and temperature
  - Relatively independent of injection pressure
- **"Memory" of conditions earlier in injection event is short**

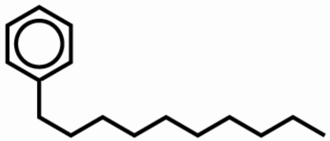
Technical Question #4: How to Better Under-stand and Predict Fuel-Composition Effects?

- **Develop more accurate diesel surrogate fuels**
  - Team assembled under Coordinating Research Council as AVFL-18
  - Led by Chuck Mueller (Sandia) and Bill Cannella (Chevron)
- **Goal is to produce a surrogate for a full-boiling-range #2 diesel fuel with matched:**
  - Ignition quality (derived cetane number)
  - Adiabatic flame temperature and EGR composition (C/H ratio)
  - Sooting tendency (% of fuel carbon in aromatic structures)
  - Distillation curve
- **4-component blending model created in FY09**
  - Used linear blending to match ignition quality, C/H ratio, and aromatic content

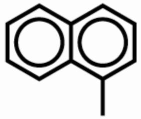
n-hexadecane ($C_{16}H_{34}$)



heptamethylnonane ($C_{16}H_{34}$)



n-decylbenzene ($C_{16}H_{26}$)



1-methylnaphthalene ($C_{11}H_{10}$)

Future Work

- **Quantify and model liquid-phase fuel penetration for pure compounds under unsteady in-cylinder conditions**
  - Heptamethylnonane and iso-octane
- **Study mixing-controlled high-efficiency clean combustion using diesel and an oxygenated fuel, < 40% EGR, and small injector orifices**
  - Relies on implementation of new high-pressure common-rail fuel-injection system
- **Investigate biodiesel feedstock effects on in-cylinder processes**
  - Liquid-phase fuel penetration
  - Combustion and emissions
- **Continue diesel surrogate fuel development (AVFL-18)**
- **Continue other active collaborations**
  - Advanced Engine Combustion Working Group, Fuels for Advanced Combustion Engines, Caterpillar

Summary

- **This fundamental fuel-effects research effort is tightly focused on a primary DOE goal of petroleum displacement, with close collaboration and guidance from industry stakeholders**

- **Significant technical accomplishments have been made during this reporting period, including:**
  - Identified mechanisms explaining NO_x increase when fueling with biodiesel
  - Showed how increasing diesel-fuel volatility can dramatically increase efficiency and decrease emissions under early-DI operating conditions
  - Established capability to quantitatively measure in-cylinder liquid-phase fuel penetration under early-DI operating conditions
  - Helped form and lead working group to develop surrogate diesel fuels for use in combustion modeling studies