SAND2008-5758C

In-Cylinder Processes of High-EGR Low-Load Diesel Combustion

Mark P. B. Musculus

Sandia National Laboratories

THIESEL 2008
Universidad Politécnica de Valencia, Spain
Thursday, September 11, 2008

Sponsor: **U.S. Dept. of Energy, Office of FreedomCAR and Vehicle Technologies**

Program Manager: **Gurpreet Singh**

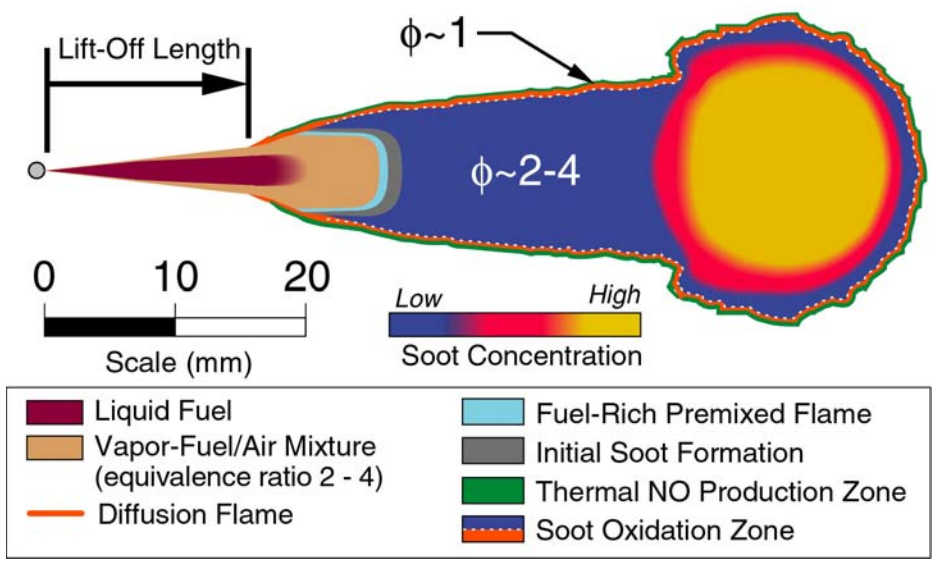
In-cylinder processes for low-temperature combustion are not yet well explored

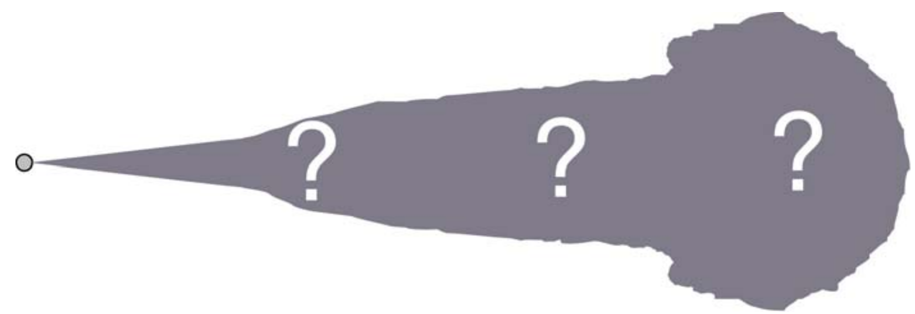
Conventional Diesel Combustion (CDC):

- No EGR, short ignition delay
- Diffusion flame (OH-PLIF) is in thin envelope surrounding jet
  - OH near ϕ~1
- Soot (LII) fills jet cross-section, where ϕ~2-4 (planar Rayleigh scattering)
  - Appearance of soot means ϕ > ~2

Low-Temperature Combustion (LTC):

- High EGR (10-15% O_2)
- Injection earlier (PPCI) or later (MK) than conventional diesel combustion
- Long ignition delay = positive ignition dwell (ignition after end of injection)
- OH, soot, ϕ, UHC, CO, NOx, etc. = ?





From SAE 970873, J. Dec,
Conceptual Model of Diesel Combustion

Compared to CDC, early-injection LTC has soot farther downstream and OH filling upstream jet

Near-TDC Inj. CDC (short ignition delay):

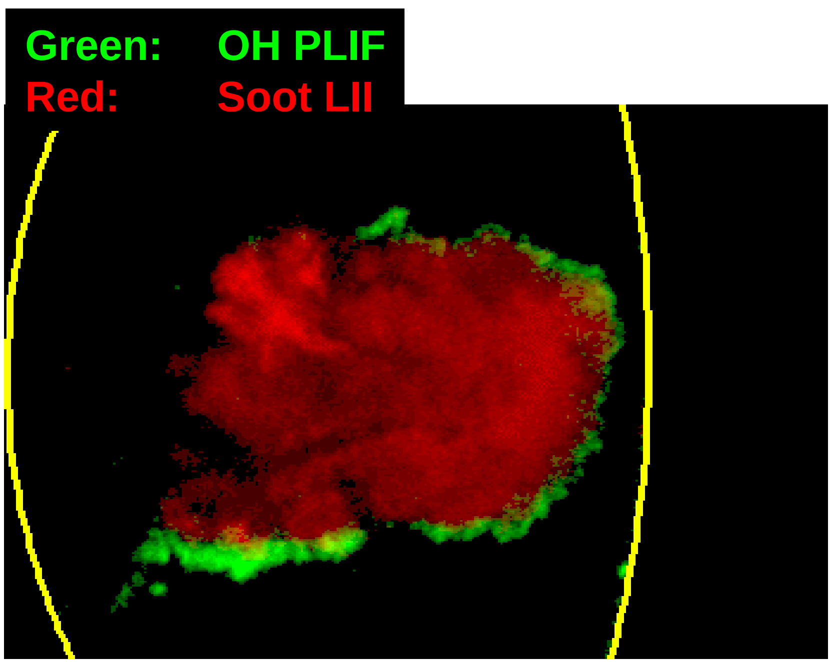
- *SAE 2001-01-1295 (Dec & Tree)*

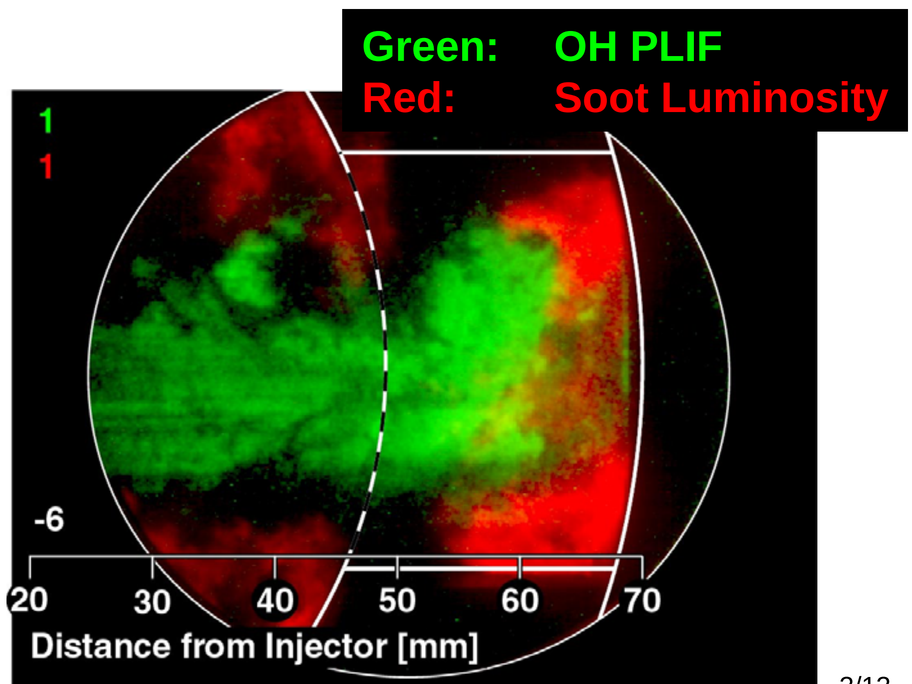
- View through cylinder head window
- OH (ϕ ~ 1, green) appears in thin envelope surrounding jet
- Soot (ϕ > 2, red) fills the jet cross-section

Early-Injection LTC (long ignition delay):

- *SAE 2006-01-0079 (Musculus)*

- OH (green) throughout jet cross-section, with soot (red) only at head of jet
- OH appears where ϕ ~ 1, and soot appears where ϕ > 2, so upstream jet is relatively lean (even with EGR!), and downstream jet is rich



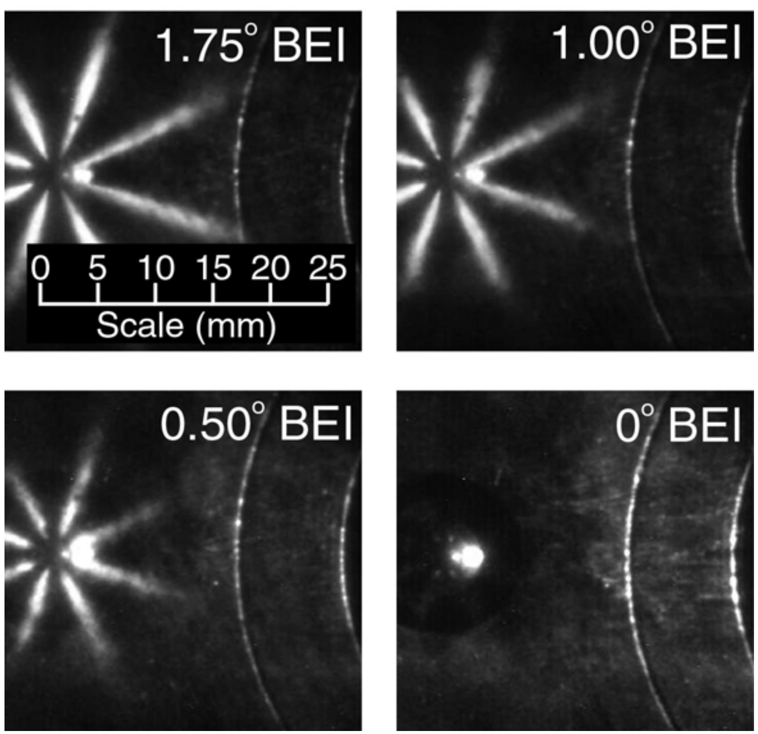


Both liquid- and vapor-fuel measurements indicate lean mixtures near injector after EOI

Liquid Fuel Near EOI (non-combusting)

- *Unpublished, but 2008 COMODIA, Kook et al. & 2009 SAE, Kook et al.*

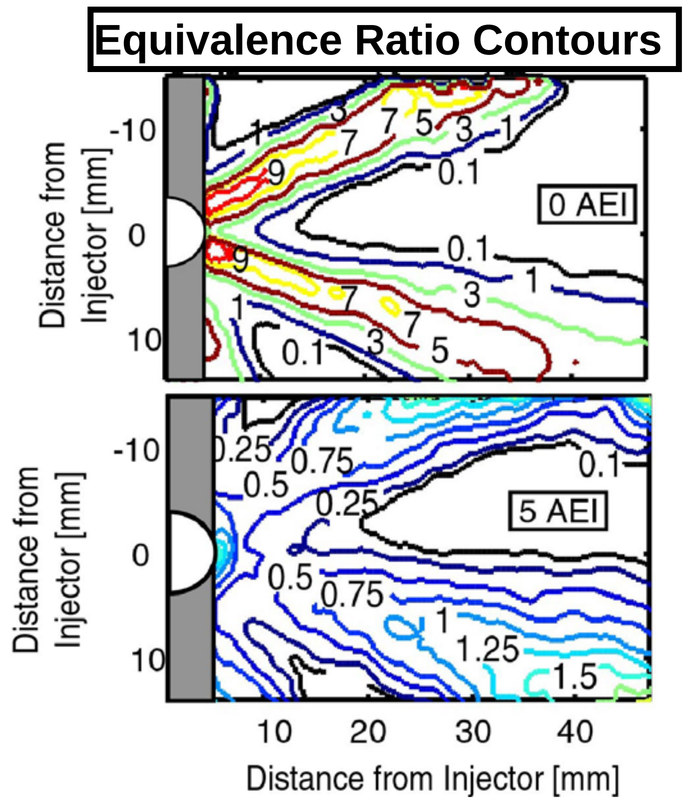
- Intake = 100% N_2, fuel = n-heptane
- During/after EOI, liquid fuel retreats back to injector
- Indicative of rapid leaning near/after EOI



Vapor Fuel Near EOI (non-combusting)

- *SAE 2007-01-0907 Musculus et al.*

- Intake = N_2, fuel = nC_7 + isoC_8 + C_7H_8
- After end of injection, mixtures near injector rapidly become fuel lean

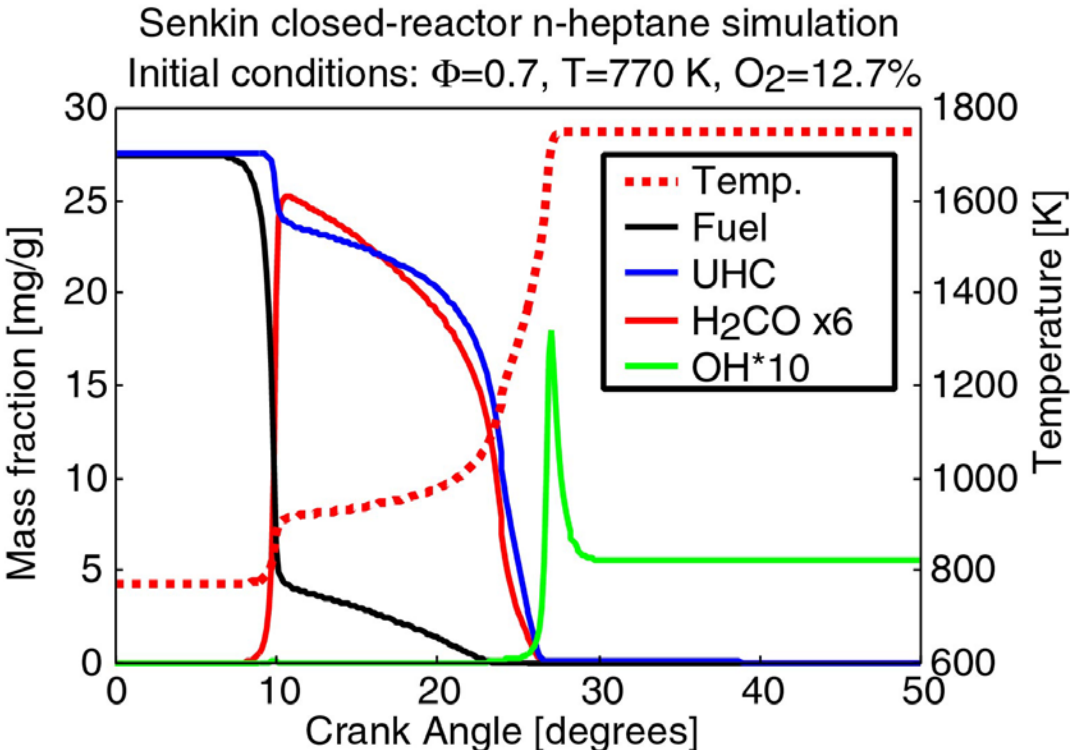


Formaldehyde indicates partially burned fuel; OH indicates complete combustion

Closed-reactor CHEMKIN simulation of n-heptane ignition using the Lawrence Livermore National Laboratories detailed mechanism of Curran, Pitz, and Westbrook

First-Stage (10 CAD):

- Much of parent fuel molecule (black) reacts, a "soup" of UHCs (blue) is formed
- **Formaldehyde (H_2CO, red) can track the soup of UHC (blue)**



Second-Stage (25 CAD):

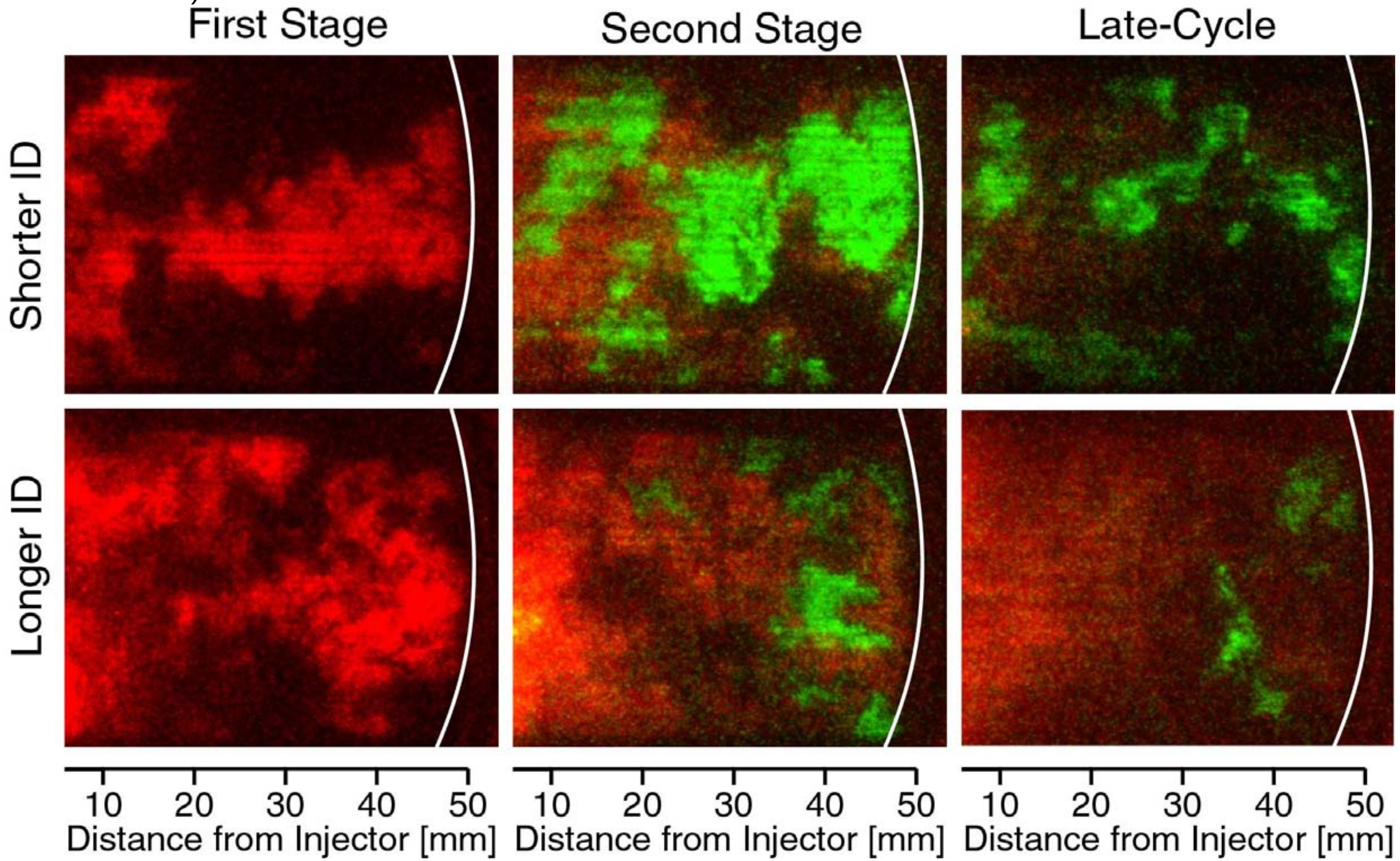
- Nearly all UHC and H_2CO consumed
- **Appearance of OH (green) marks hot ignition and consumption of UHC**

H_2CO and OH show late-cycle UHC remains near injector for conditions with long ignition delay

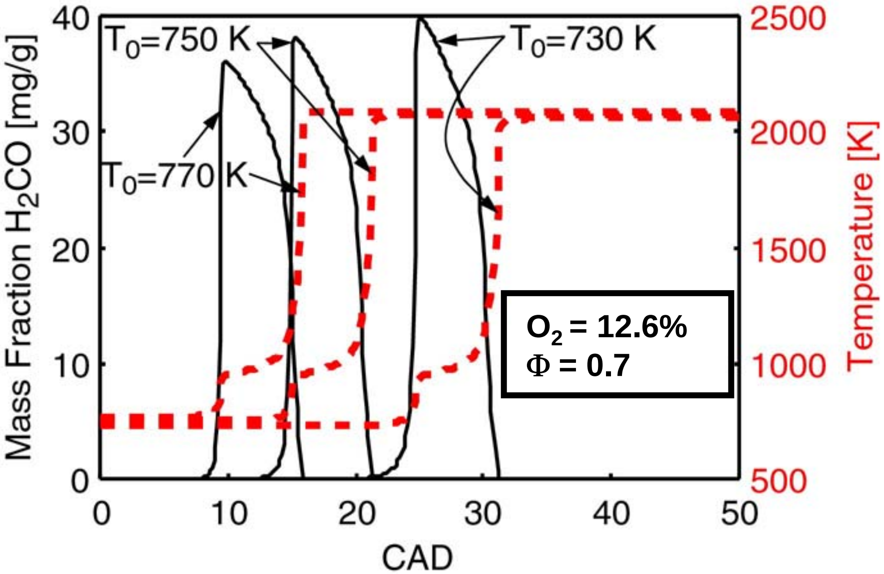
Red = Formaldehyde (H_2CO) fluorescence, Green = OH Fluorescence

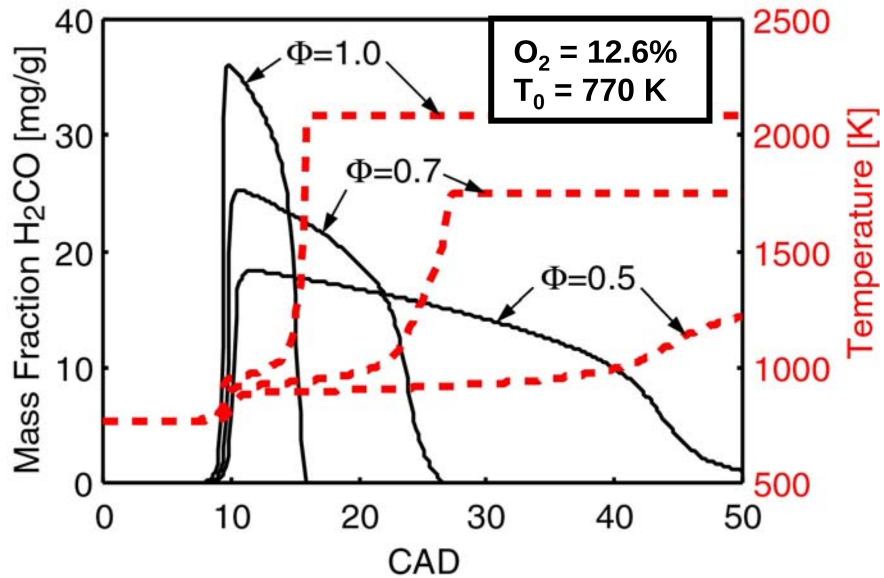
For Shorter ID, OH appears as H_2CO & UHC near injector are consumed

For Longer ID, OH appears only downstream and H_2CO & UHC remain late in the cycle, especially near injector – (Western States Comb. Inst. Meeting, 2007, Musculus & Lachaux)



Simulations show that formaldehyde persists in lean regions, but not necessarily in cool regions



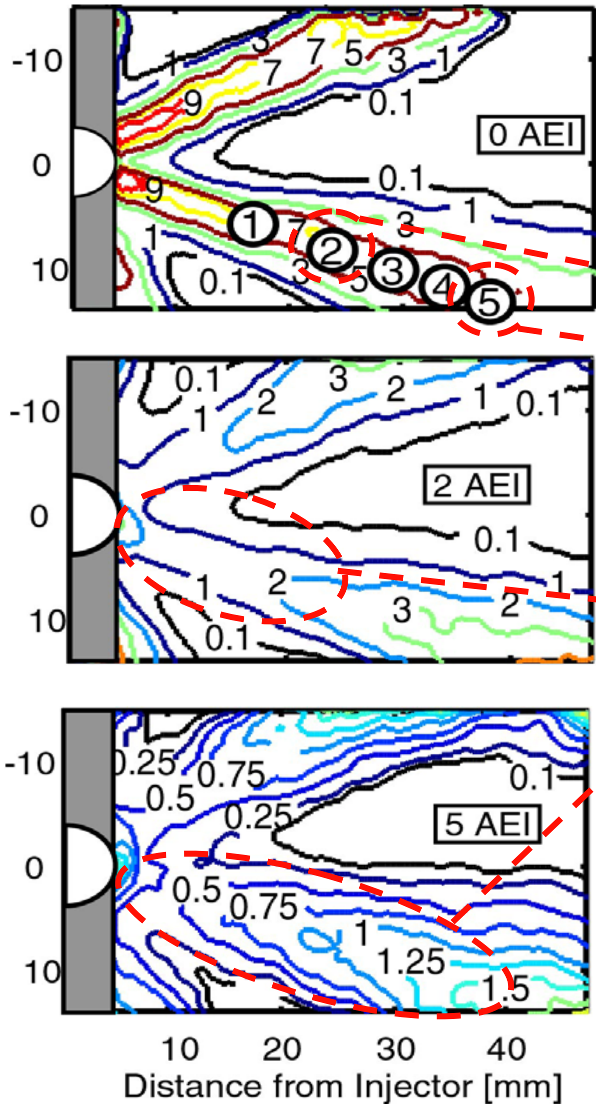


- Q: Is late formaldehyde caused by (1) low temperatures or (2) lean mixtures?
- (1): As temperature is decreased, H_2CO appearance is delayed, but residence time is constant.
- (2): As equivalence ratio is decreased, H_2CO time of appearance is constant, but residence time is increased.
- **Therefore, regions that have long-lasting, late-cycle H_2CO fluorescence are likely lean (near injector, after injection).**

Closed-reactor CHEMKIN simulations of n-heptane ignition using the Lawrence Livermore National Laboratories detailed mechanism of Curran, Pitz, and Westbrook

Mixing after EOI is more rapid than in a steady jet

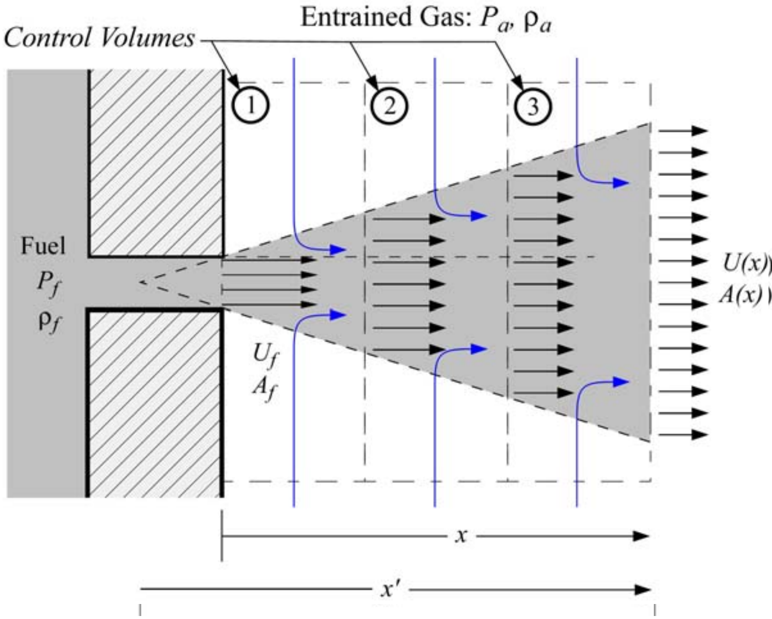
(SAE 2007-01-0907, Musculus et al.)

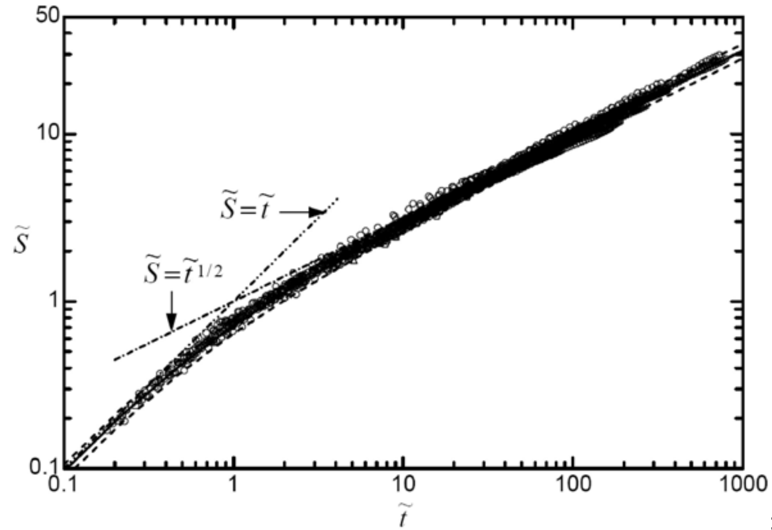


- At end of injection (0 AEI), mixtures are richer near injector (ϕ ~ 9) and leaner downstream
- In the quasi-steady jet, from a Lagrangian perspective (moving with jet fluid at penetration rate):
  - After 2° crank angle, ϕ = 5 to 7, and
  - After 5° crank angle, ϕ = 3 to 5
- After end of injection, mixtures near injector are much leaner than expected for downstream transport in a steady jet
  - At 2 AEI, within 25 mm penetration, ϕ = 1 to 3
  - At 5 AEI, within 45 mm penetration, ϕ = 0.5 - 1.5
    - > Downstream mixtures agree with OH filling jet cross section (ϕ ~ 1 for OH)
    - > Upstream mixtures near injector agree with late-cycle formaldehyde (ϕ ~ 0.5)

Transient diesel-jet mixing may be analyzed using 1-dimensional control volume array

- Analytical control-volume solution for diesel jet penetration and mixing:
  Naber and Siebers, SAE 960034
- Predicts experimental penetration over wide range of conditions
- No similar analytical control-volume solution for non-steady injection rates
- However, non-steady jets can be solved numerically
  - 1-dimensional control volume array
  - Assume radial profiles for velocity and fuel concentration
  - Solve transient mass and momentum transport between control volumes
  - Similar approach as CMT article *(Fuel 87, 2871-2885 (2008) "A 1D model for the description of mixing-controlled inert diesel sprays," Pastor et al.)*

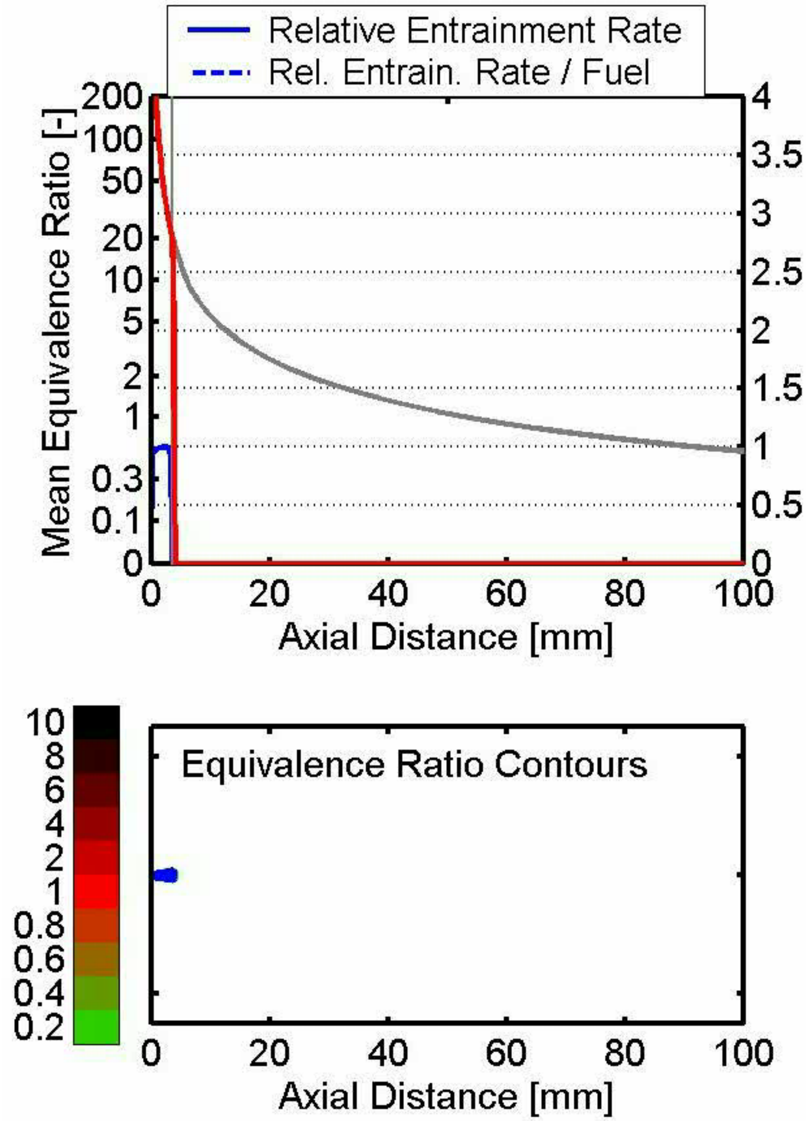




Model predicts that entrainment increases after the end of injection, in a wave that travels downstream

1-D Diesel Jet Model *(SAE 2009, Musculus et al.)*

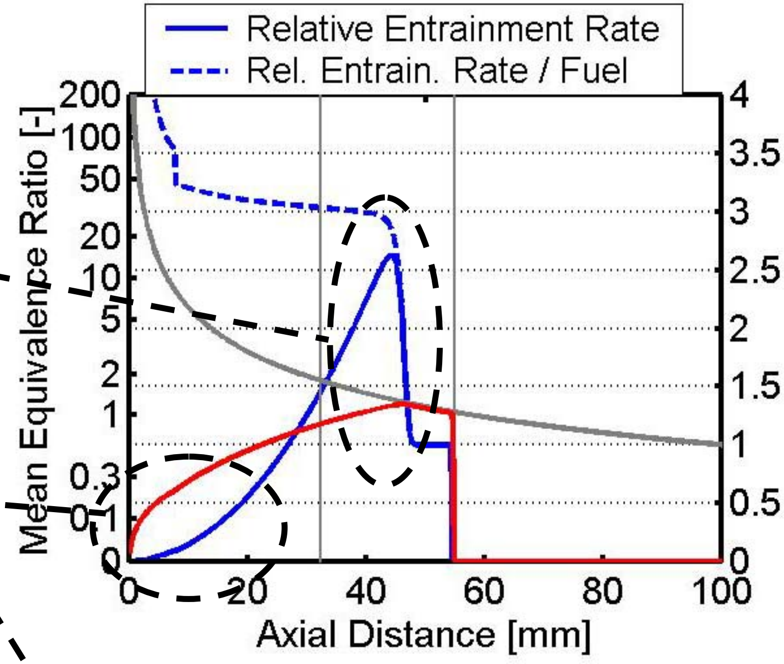
- Solves conservation of mass and momentum for 1-D control volume array

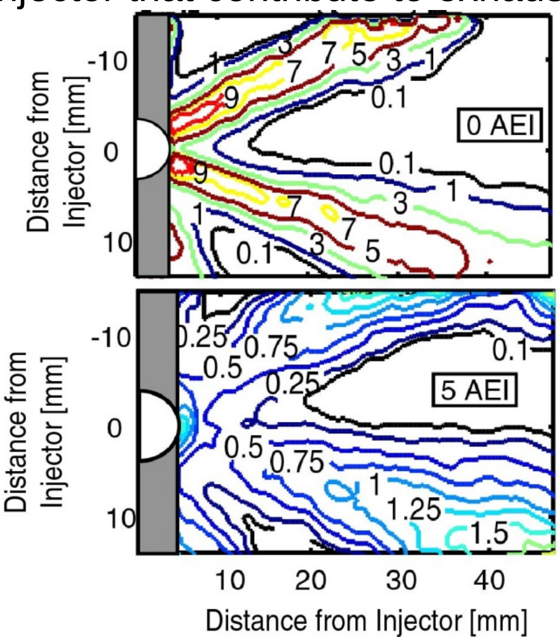


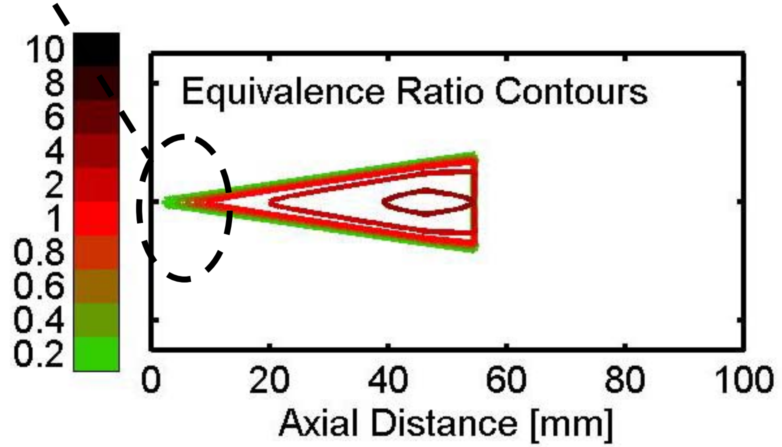
The "entrainment wave" concept explains many observed phenomena in ending diesel jets

1-D Diesel Jet Model *(SAE 2009, Musculus et al.)*

- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An "entrainment wave" travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an <u>output</u> of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC



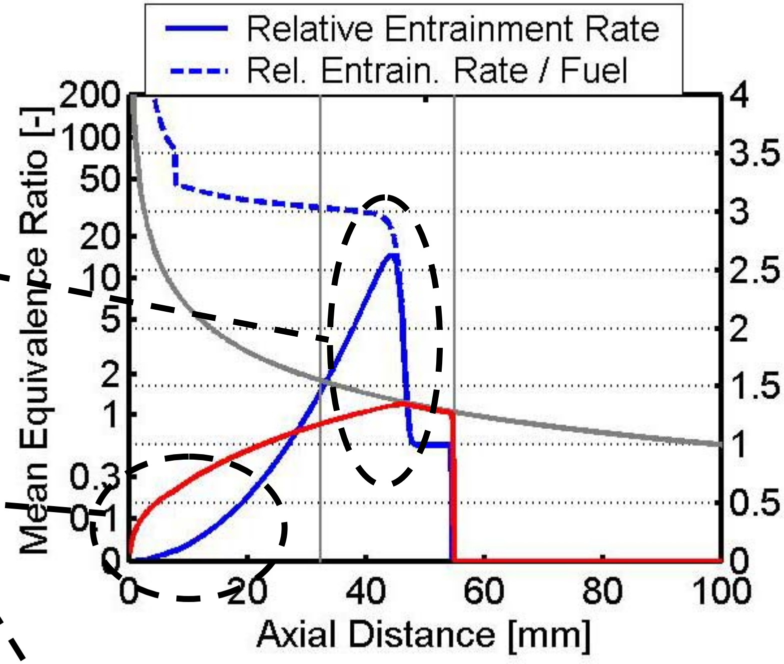


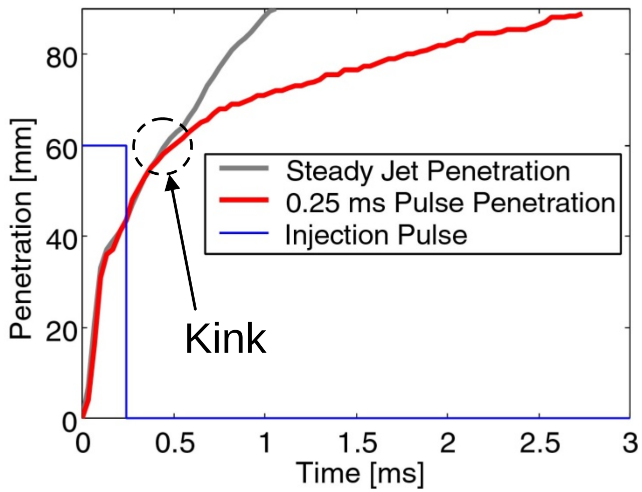


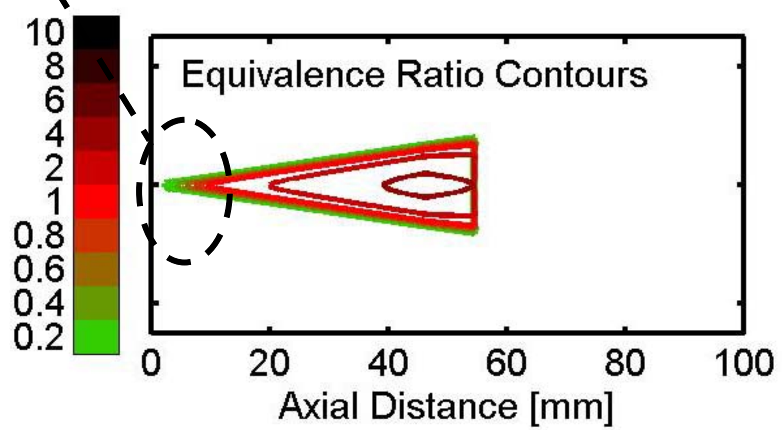
The "entrainment wave" concept explains many observed phenomena in ending diesel jets

1-D Diesel Jet Model *(SAE 2009, Musculus et al.)*

- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An "entrainment wave" travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an <u>output</u> of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC
  - 2. Explains penetration "kink" at t=2xDOI (wave propagates at 2x jet penetration)



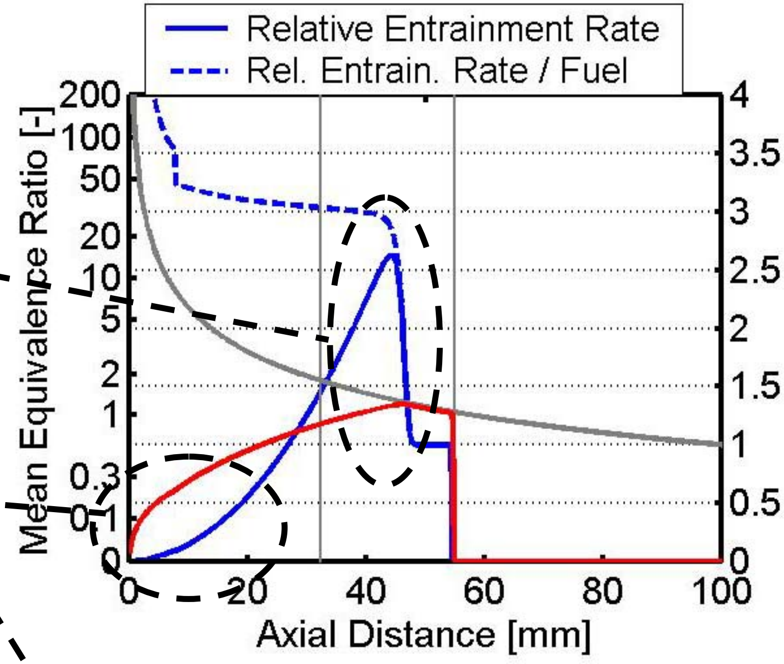


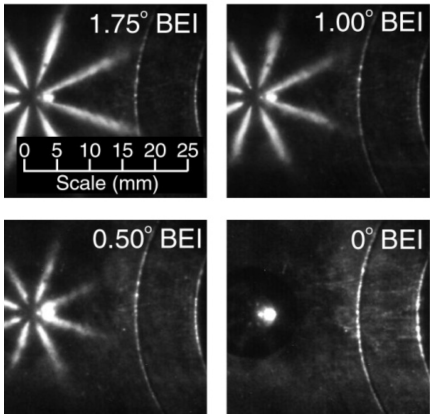


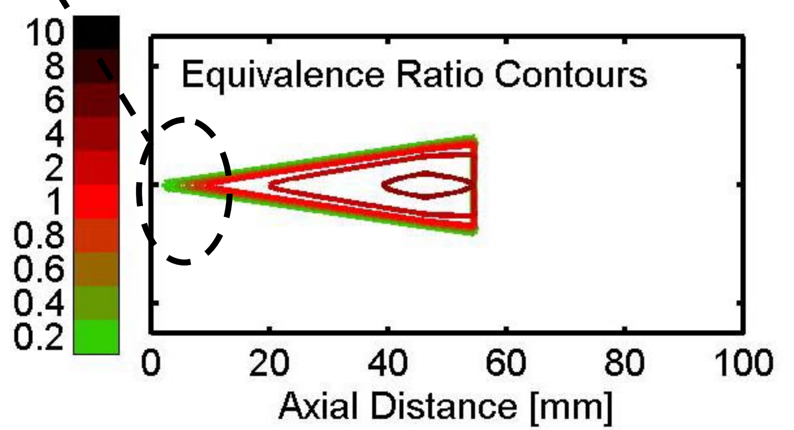
The “entrainment wave” concept explains many observed phenomena in ending diesel jets

1-D Diesel Jet Model *(SAE 2009, Musculus et al.)*

- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An “entrainment wave” travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an <u>output</u> of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC
  - 2. Explains penetration “kink” at t=2xDOI (wave propagates at 2x jet penetration)
  - 3. Explains liquid-fuel vaporization behavior after EOI (retreat, detach, split)



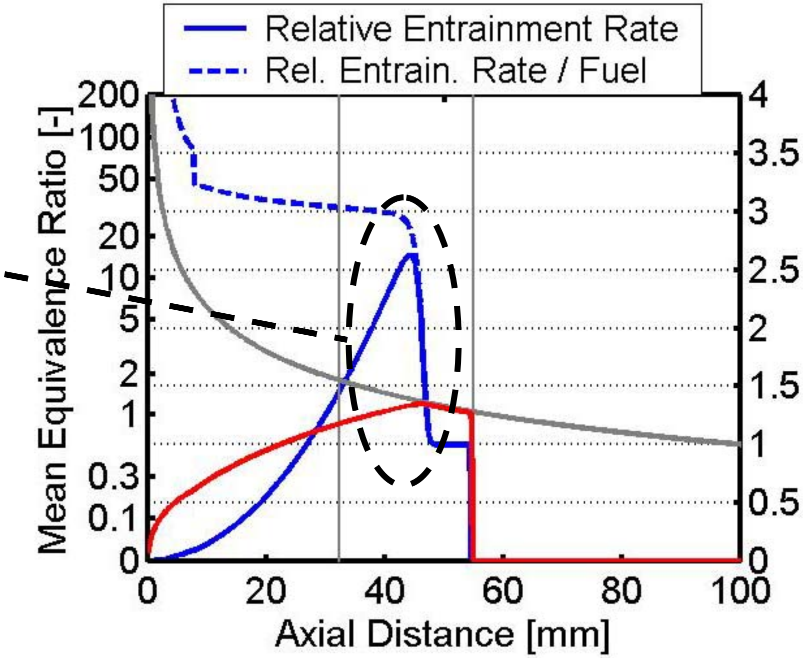


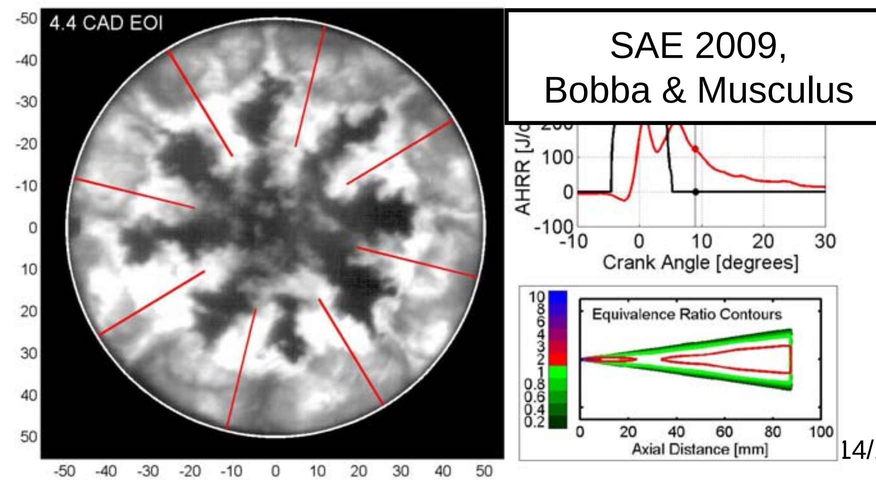


The "entrainment wave" concept explains many observed phenomena in ending diesel jets

1-D Diesel Jet Model *(SAE 2009, Musculus et al.)*

- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An "entrainment wave" travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an <u>output</u> of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC
  - 2. Explains penetration "kink" at t=2xDOI (wave propagates at 2x jet penetration)
  - 3. Explains liquid-fuel vaporization behavior after EOI (retreat, detach, split)
  - 4. Explains rapid oxidation of soot in the upstream jet after the end of injection



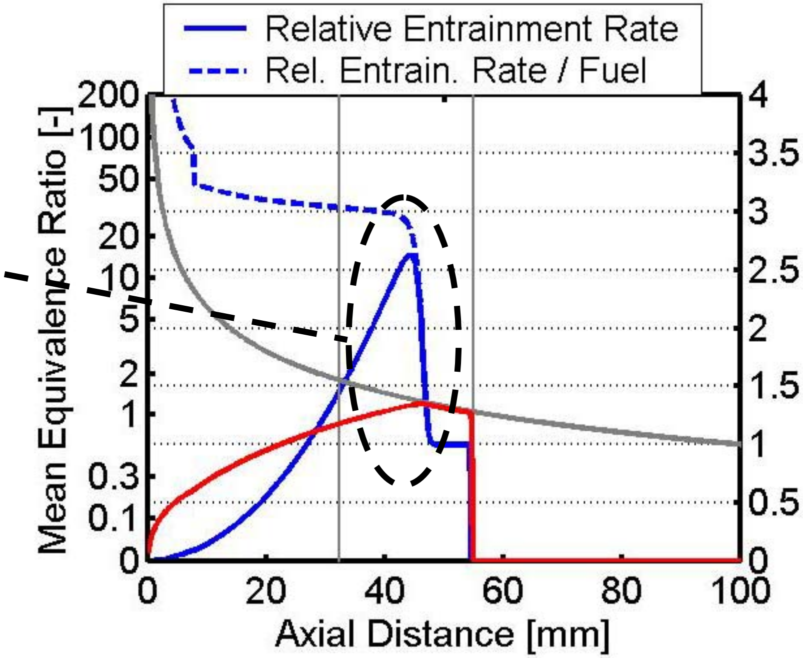


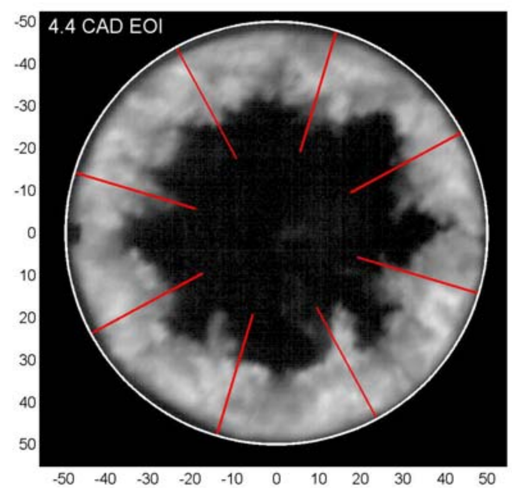
SAE 2009,
Bobba & Musculus

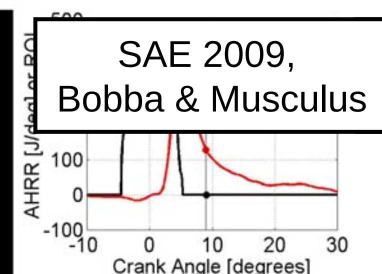
The “entrainment wave” concept explains many observed phenomena in ending diesel jets

1-D Diesel Jet Model *(SAE 2009, Musculus et al.)*

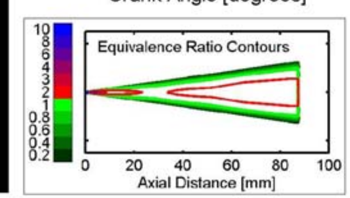
- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An “entrainment wave” travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an <u>output</u> of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC
  - 2. Explains penetration “kink” at t=2xDOI (wave propagates at 2x jet penetration)
  - 3. Explains liquid-fuel vaporization behavior after EOI (retreat, detach, split)
  - 4. Explains rapid oxidation of soot in the upstream jet after the end of injection
  - 5. Explains lack of soot formation in upstream jet with long ignition dwell







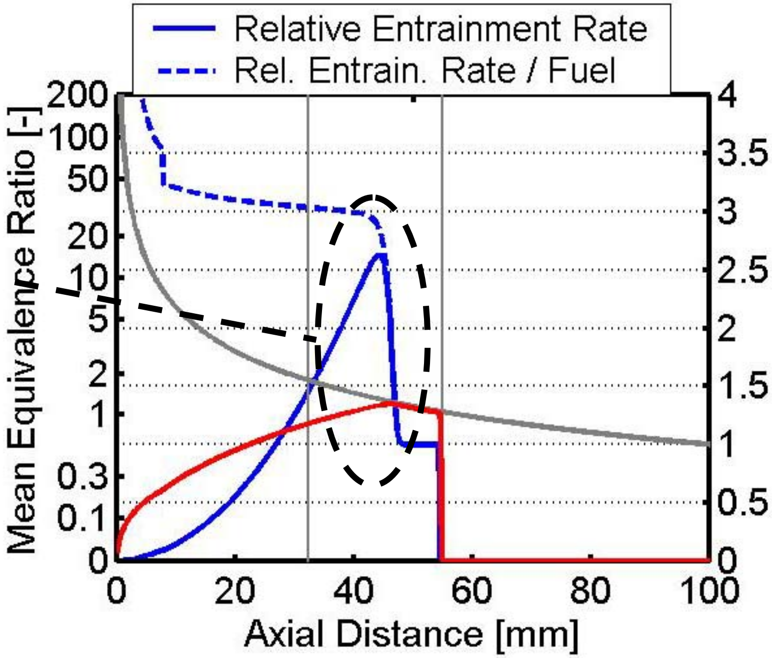
SAE 2009,
Bobba & Musculus

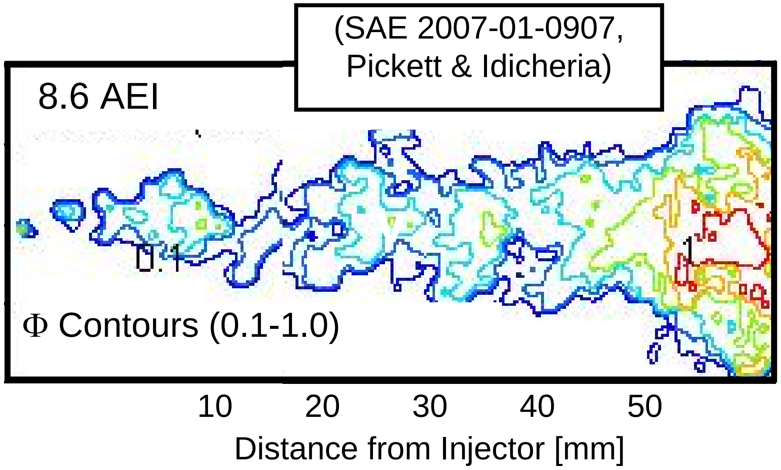


The "entrainment wave" concept explains many observed phenomena in ending diesel jets

1-D Diesel Jet Model *(SAE 2009, Musculus et al.)*

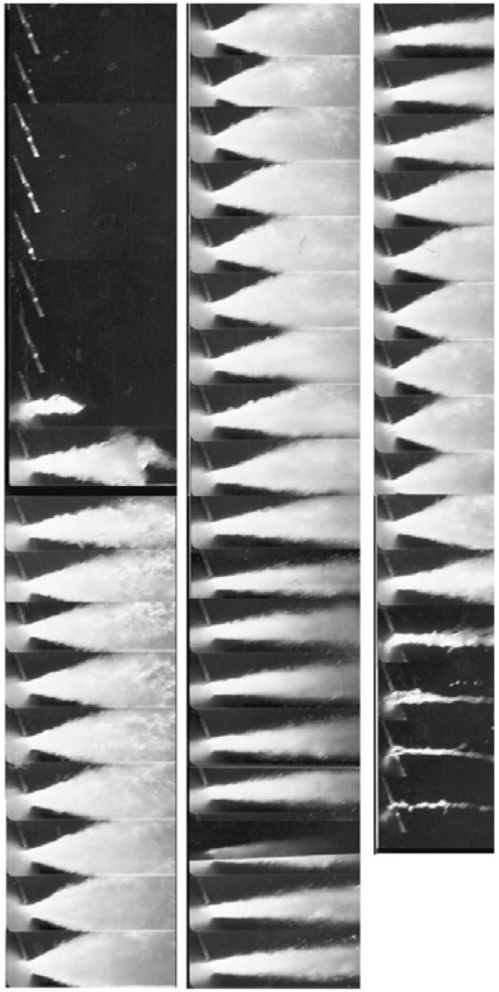
- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An "entrainment wave" travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an output of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC
  - 2. Explains penetration "kink" at t=2xDOI (wave propagates at 2x jet penetration)
  - 3. Explains liquid-fuel vaporization behavior after EOI (retreat, detach, split)
  - 4. Explains rapid oxidation of soot in the upstream jet after the end of injection
  - 5. Explains lack of soot formation in upstream jet with long ignition dwell
  - 6. Explains stagnant region near injector after end of injection





To fully realize the potential of LTC, we need better understanding of diesel-jet mixing during/after EOI

- Mixing <u>after</u> the end of injection is critical for preparing mixtures prior to ignition
  - Increased mixing of fuel with ambient gas is essential to reduce soot formation, but …
  - Too much mixing can lead to over-lean mixtures, incomplete combustion, and UHC + CO emissions
- The end-of-injection transient diesel spray can be very different from the quasi-steady spray
- During and after the end of injection,
  - How/why does the spray angle change?
  - How/why does entrainment increase?
  - How/why do the velocity and flow area change?
  - How/why does the shape of the end-of-injection ramp-down affect mixing?
  - How/why do in-cylinder turbulence and bulk flow structures affect mixing?
  - How/why do all of these phenomena vary for different injectors and facilities?

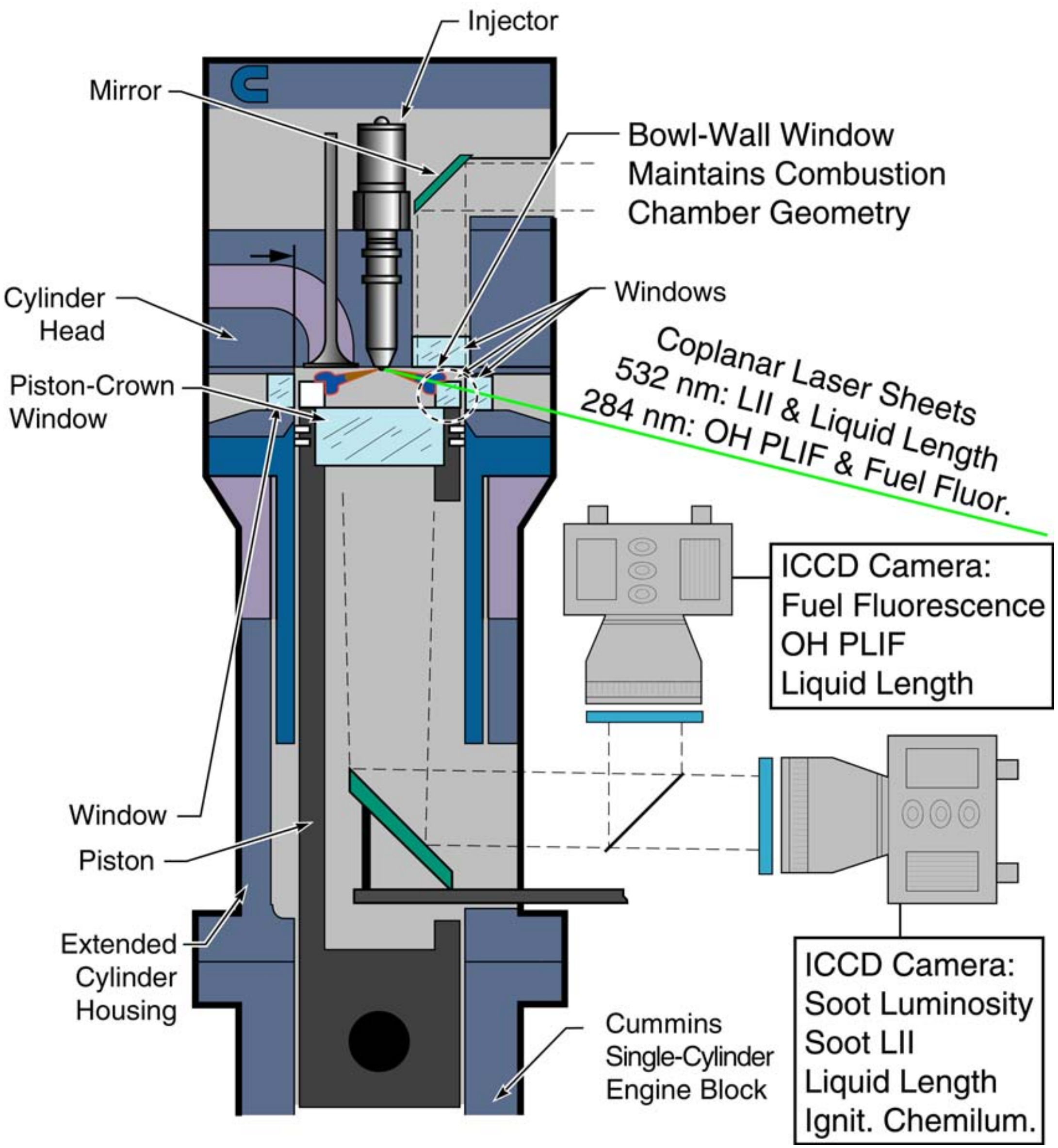


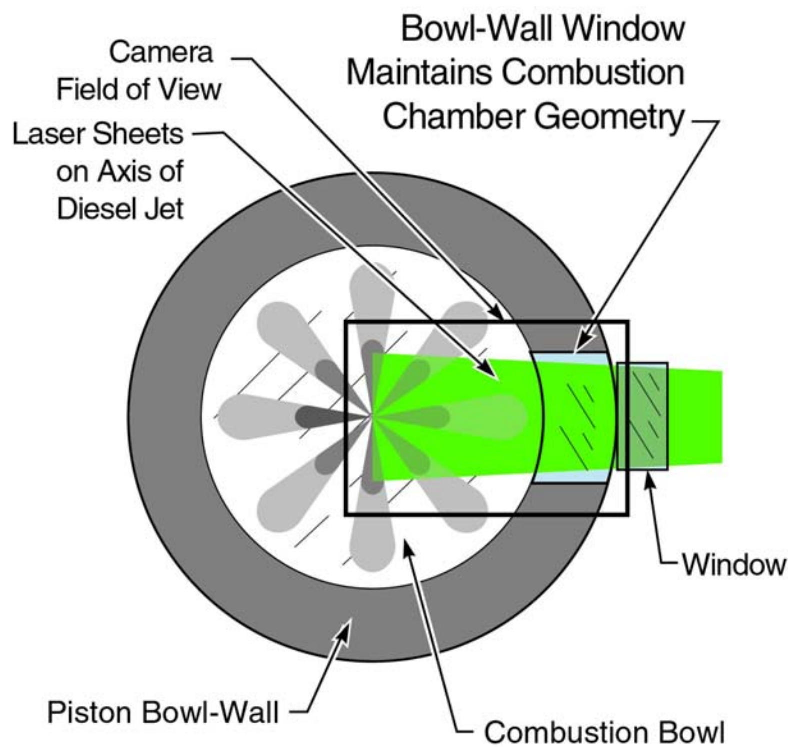
From SAE 2000-01-1256, Han et al.
(Wayne State University, USA)

Simultaneous Diagnostics

Use two laser-sheets and two cameras for simultaneous imaging

Can use either a cut-out or a window in the piston bowl-wall to allow laser access within piston bowl of combustion chamber

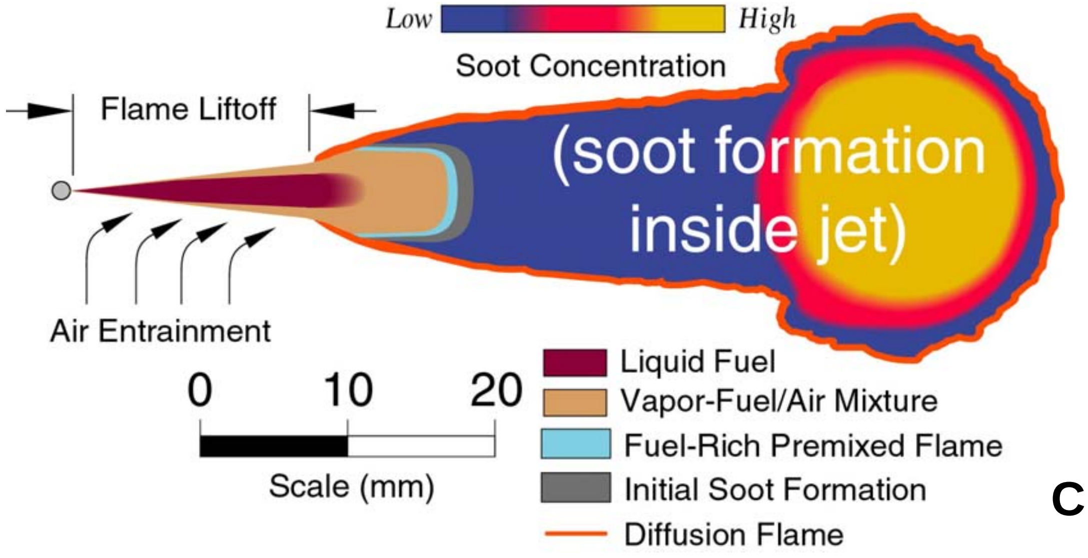




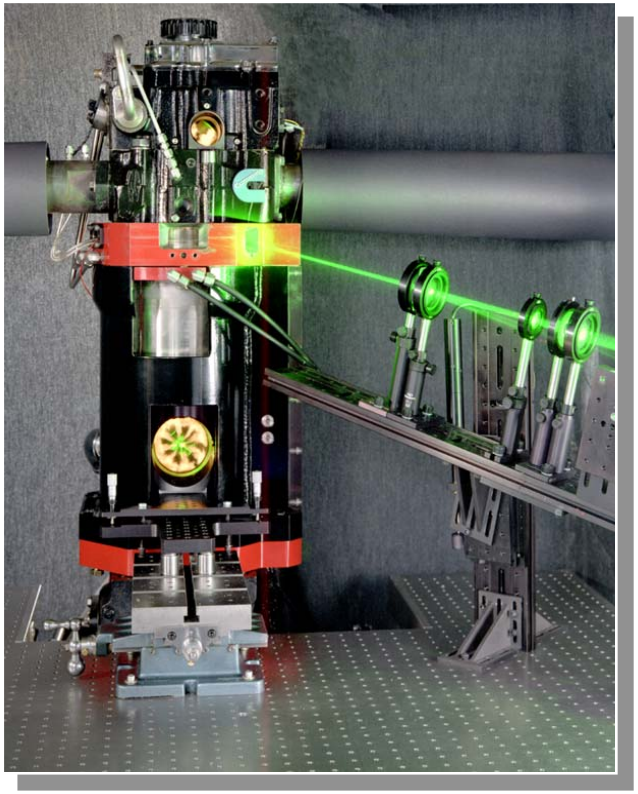
Top View of Piston

Project Overview:
Sandia/Cummins Heavy-Duty Optical Engine

Background: Since late 1980's, in-cylinder diesel spray, combustion, and pollutant formation has been studied at Sandia with multiple laser/optical diagnostics. Data is basis of conceptual model of conventional diesel combustion.



From SAE 970873, J. Dec,
Conceptual Model of Diesel Combustion



Current Status: New high-pressure common-rail fuel-injection system, enabling study of advanced, low-temperature, multi-mode combustion schemes.