In-Cylinder Processes of EGR-Diluted Low-Load, Low-Temperature Diesel Combustion

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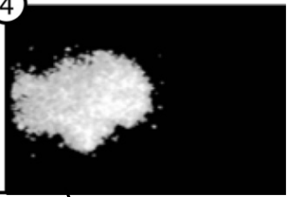
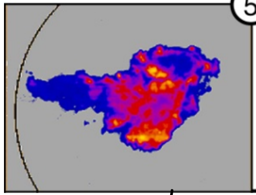
Conventional diesel in-cylinder processes have been revealed by optical diagnostics

O_2 = 21% (no EGR)
SOI = 10 BTDC
P_{inj} = 1000 Bar

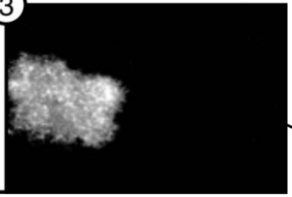
4 — PAH PLIF: Soot Precursors
As hot ignition reactions increase the temperature in the jet, fuel fragments are formed into chemical building blocks for soot.



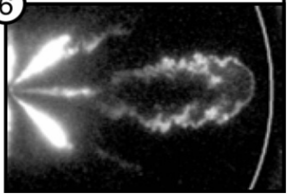
5 — LII: Soot Concentration
Shortly after the premixed fuel burns, soot is formed in the hot, fuel-rich region throughout the jet cross-section.



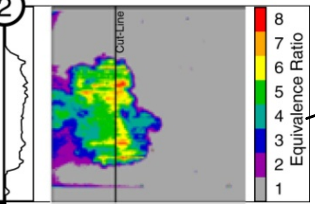
3 — Chemiluminescence: Ignition
Spontaneous ignition reactions occur in the hot mixture of fuel and air throughout the leading portions of the jet.

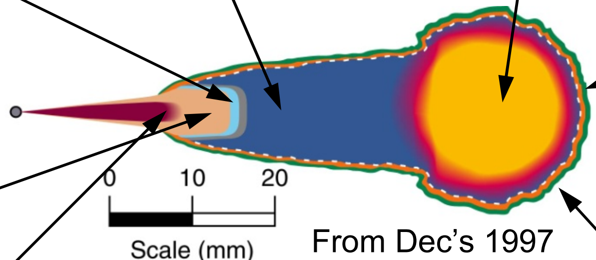


6 — OH PLIF: Diffusion Flame
Shortly after the premixed fuel burns, a thin diffusion flame forms on the jet periphery, surrounding the interior soot cloud.



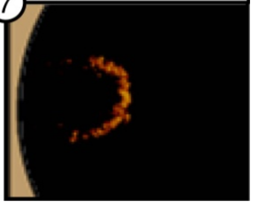
2 — Rayleigh Scatter: Vapor Fuel
The vaporized fuel-air mixture downstream of the liquid is relatively uniform and fuel-rich (Φ = 2-4).



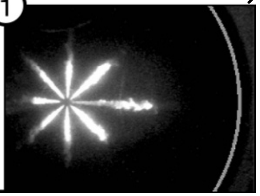


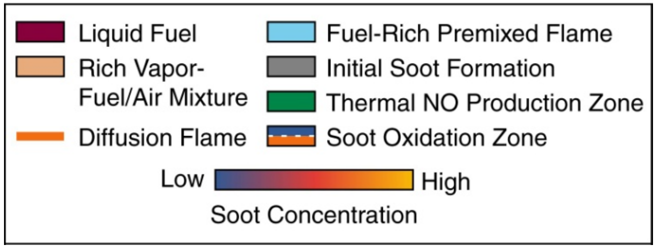
From Dec's 1997 conceptual model (SAE 970873).

7 — NO PLIF: Thermal NO
NO forms on the periphery of the jet in the hot diffusion-flame products.



1 — Mie Scatter: Liquid Fuel
After penetrating approx. 25 mm, the hot, entrained gases completely vaporize the liquid fuel.



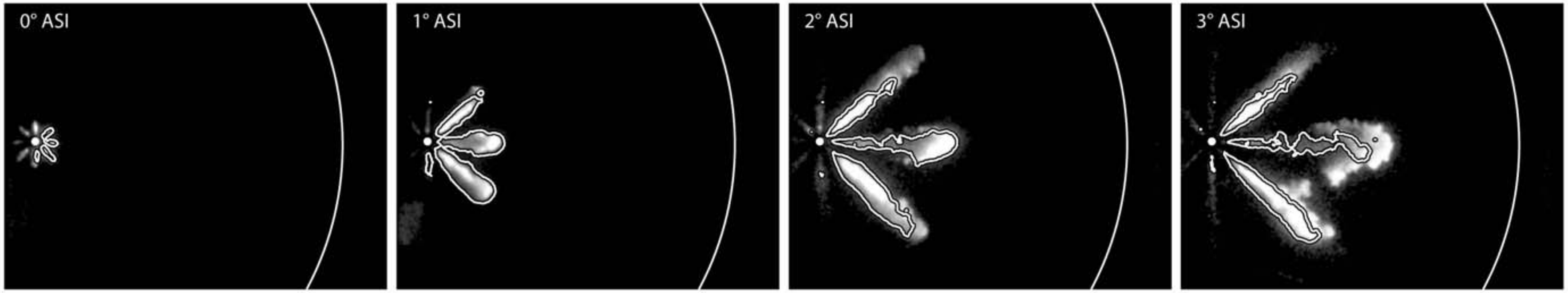


Liquid fuel “retreat” after EOI indicates greater mixing after EOI

- Initial liquid- and vapor-fuel penetration similar to conventional diesel
- After end of injection (EOI), fuel vaporizes rapidly, starting downstream first

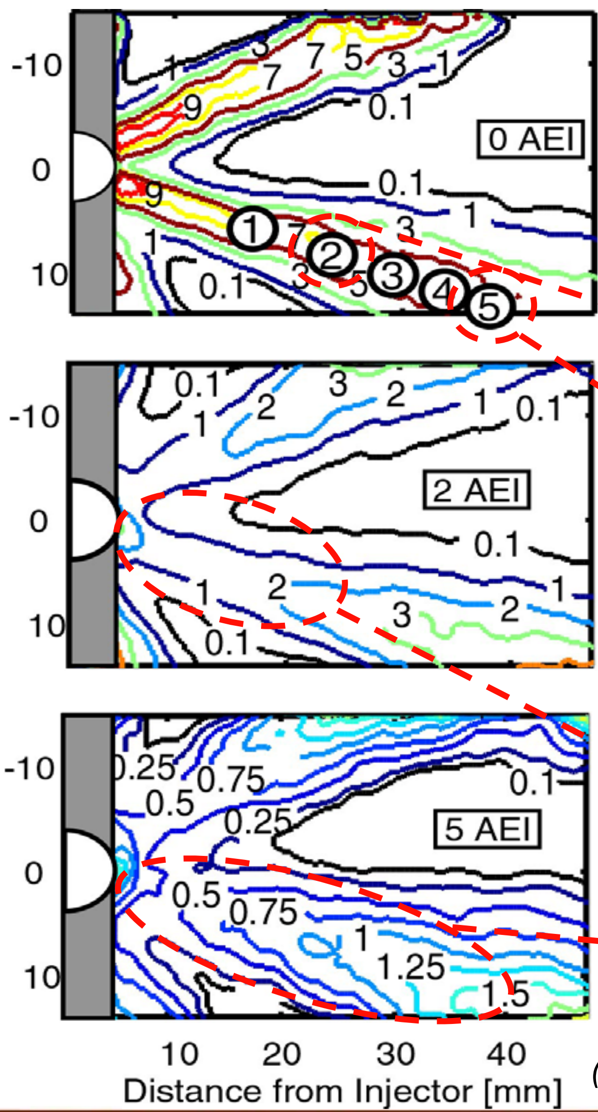
O_2	= 13% (high EGR)
SOI	= 22 BTDC
P_{inj}	= 1200 Bar

- “Retreat” of liquid fuel consistent with greater mixing of hot gases



* Contour = liquid fuel Mie scatter; Grayscale = leading-edge vapor-fuel fluorescence

Fuel-tracer fluorescence shows near-injector mixtures rapidly become fuel-lean after EOI

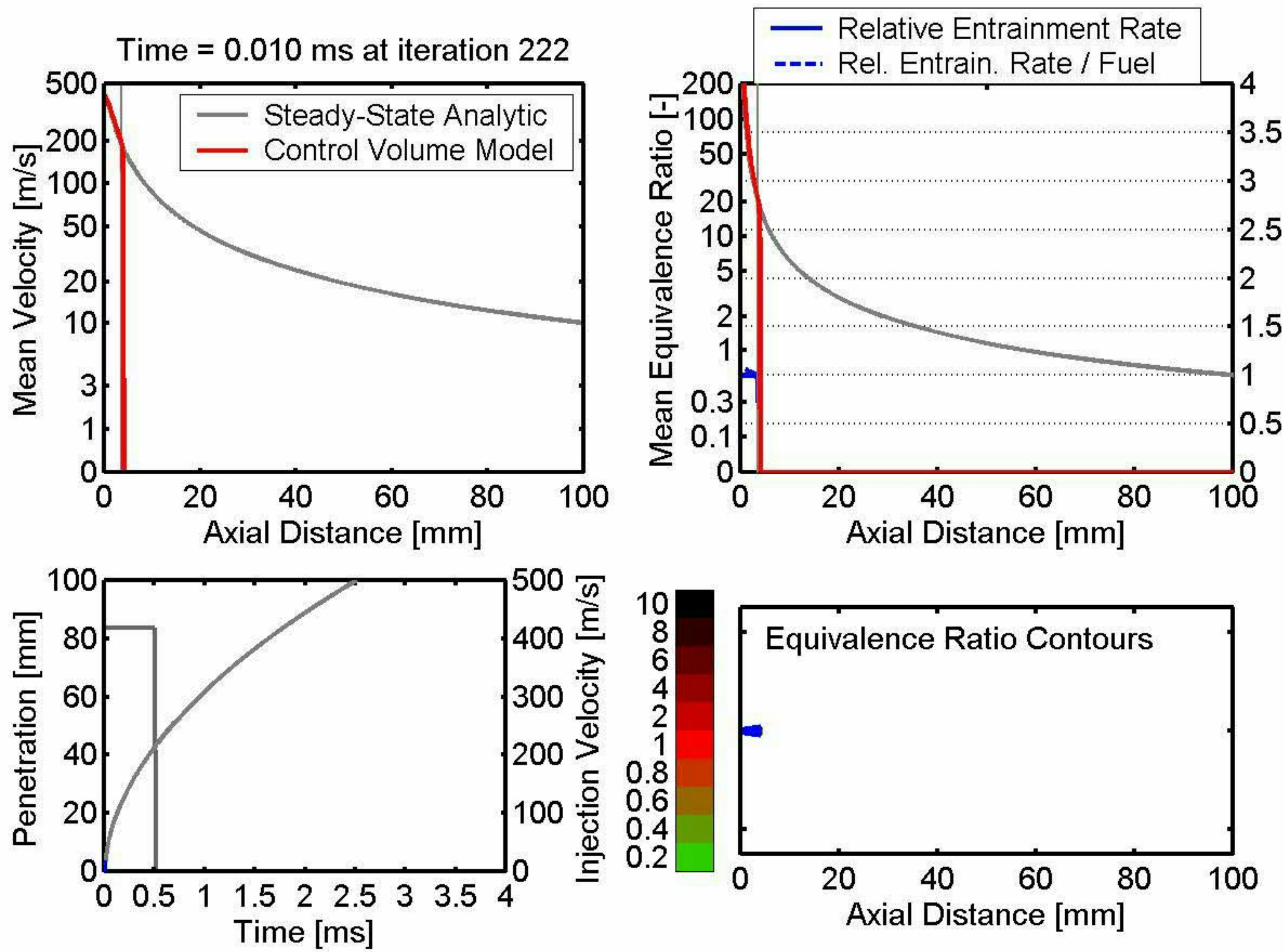


- At end of injection (0 AEI), mixtures are richer near injector (ϕ ~ 9) and leaner downstream
- In the quasi-steady jet, from a Lagrangian perspective (moving with jet fluid at penetration rate):
  - After 2° crank angle, 25 mm penetration to ϕ = 5 to 7
  - After 5° crank angle, 45 mm penetration to 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

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

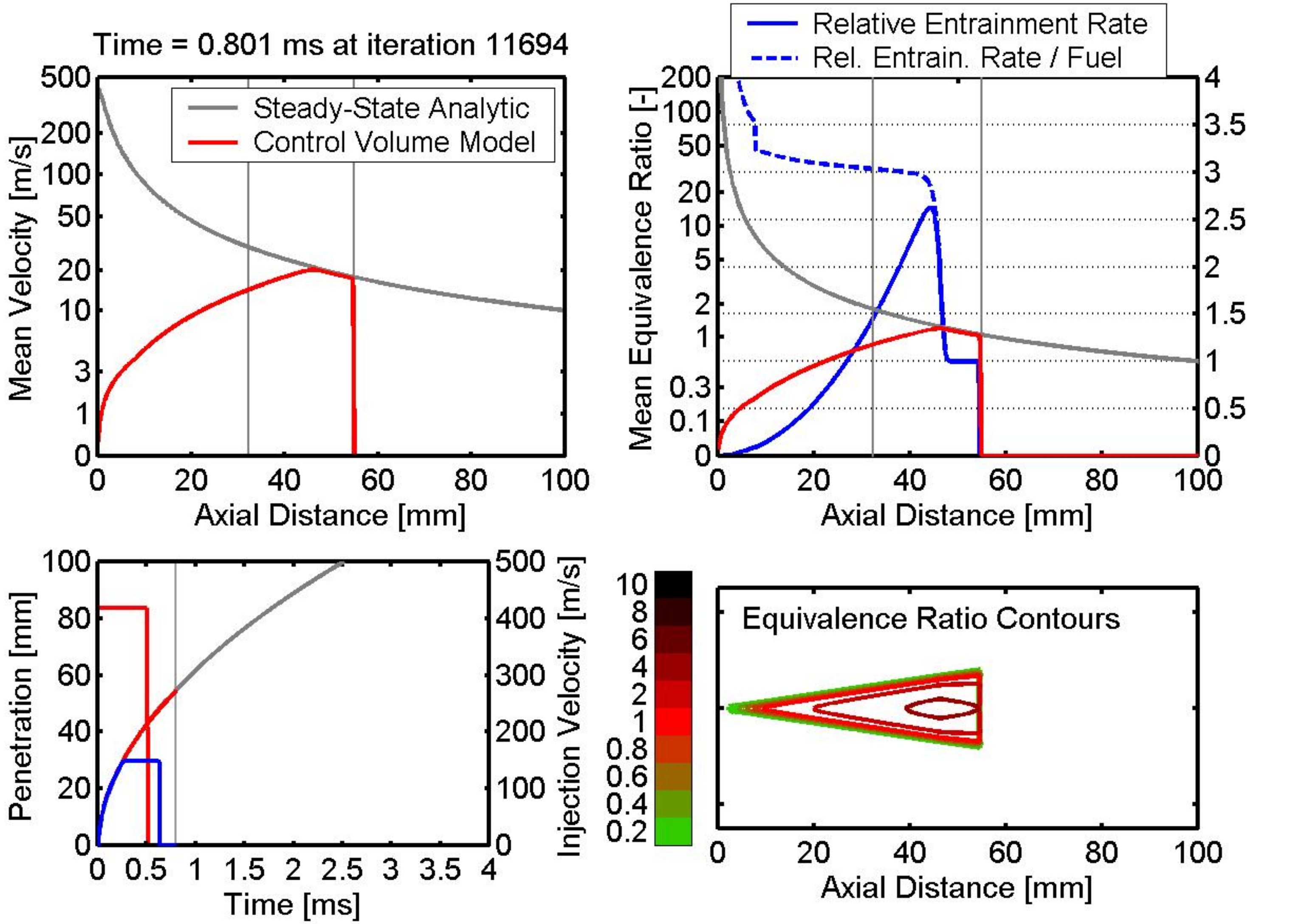
1-D control-volume model predicts a temporary wave of increased entrainment after EOI

(SAE 2009-01-1355)



The entrainment wave creates lean mixtures near the injector

(SAE 2009-01-1355)

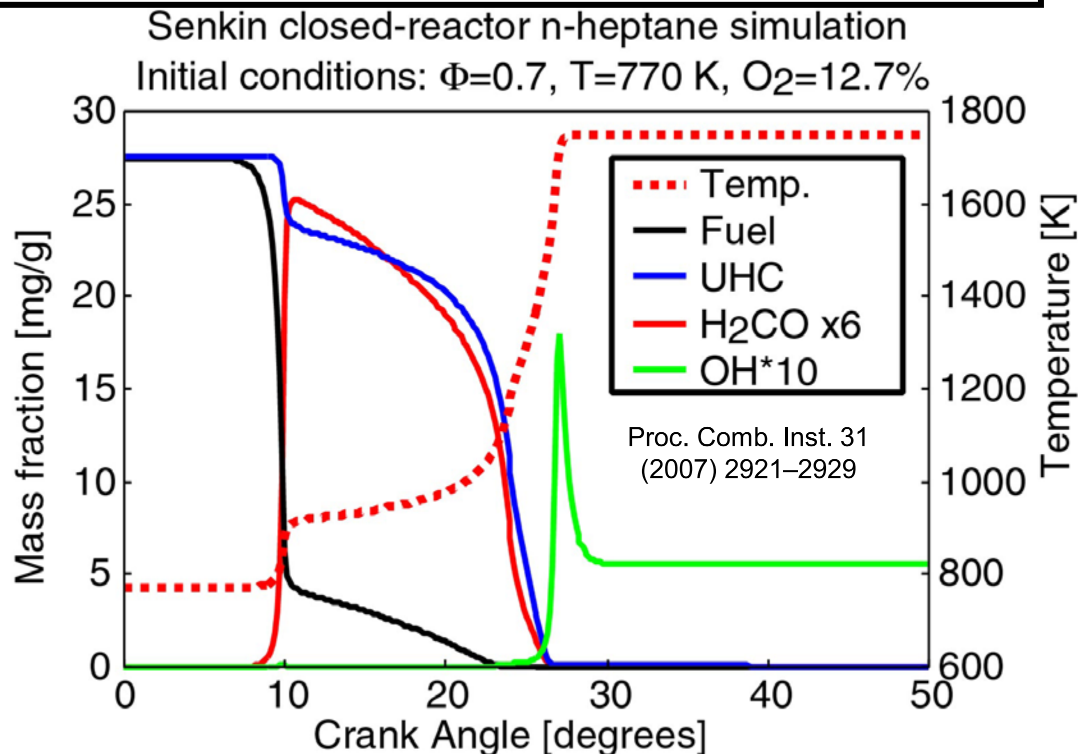


Formaldehye is a naturally occurring tracer for fuel between 1st and 2nd stages of ignition

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 the **parent fuel molecule (black)** reacts, and 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**

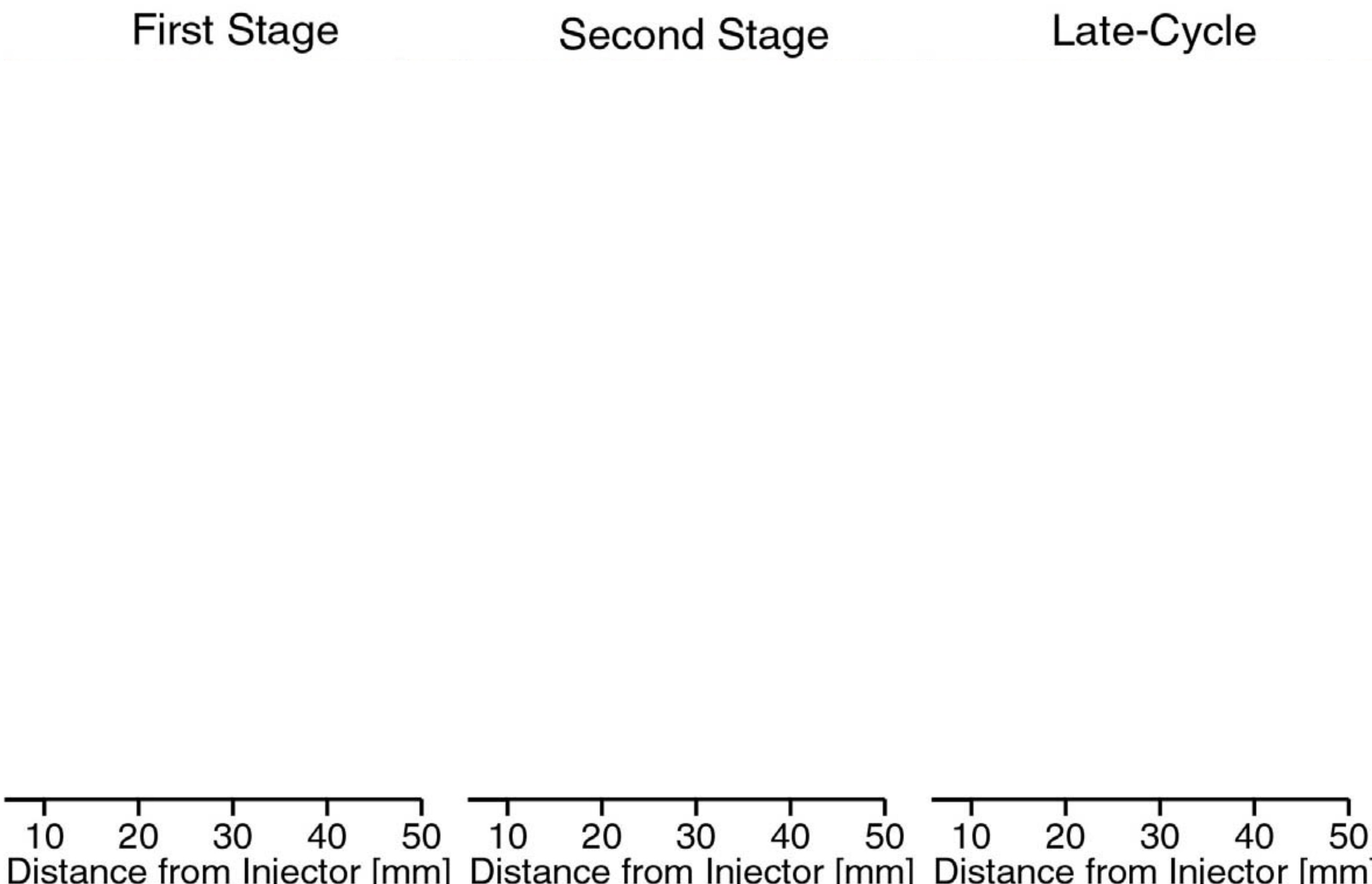
For longer ignition dwell, formaldehyde PLIF shows UHC remains near injector late in the cycle

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

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

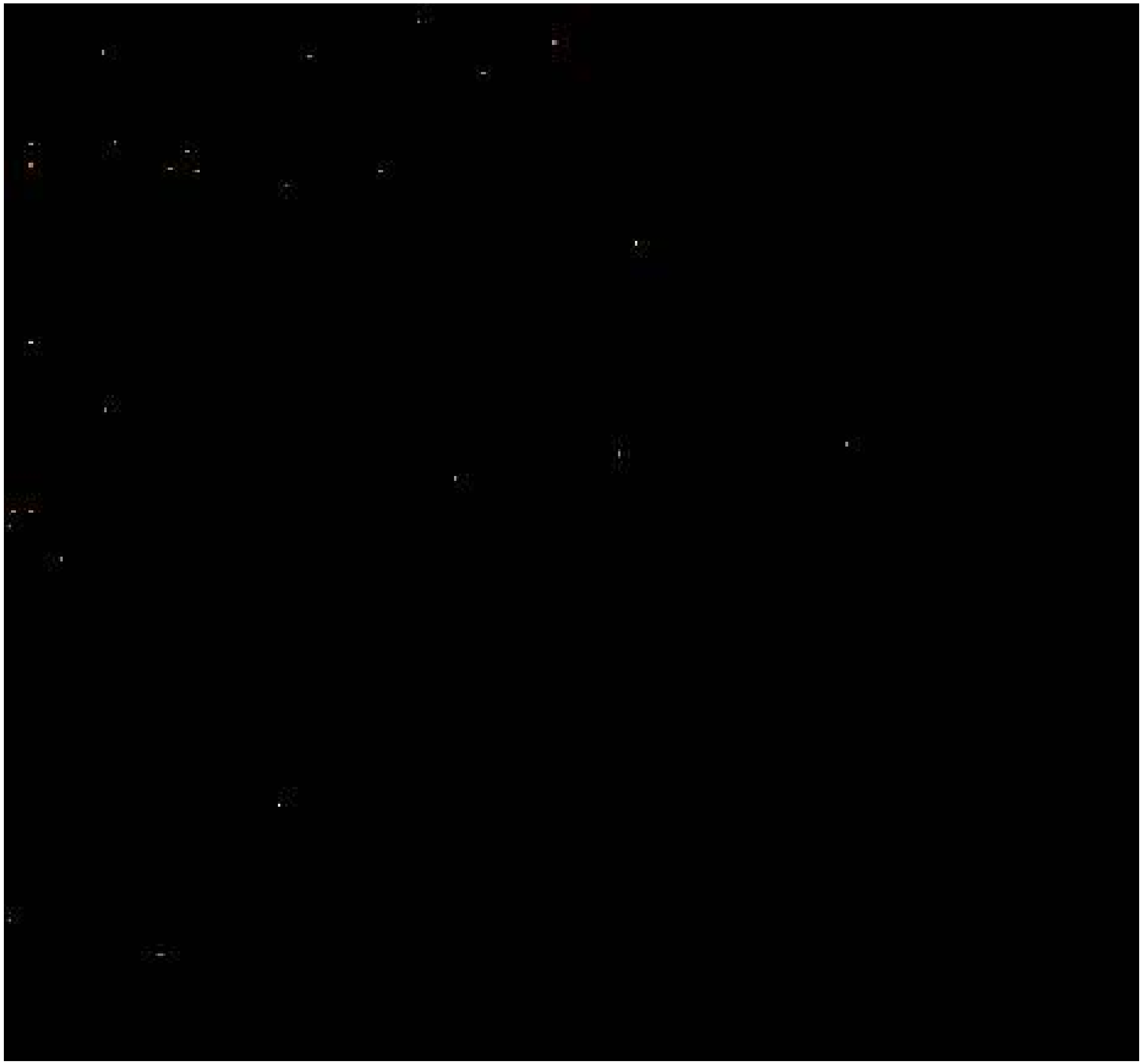
For Longer ID, H_2CO & UHC remain late in the cycle, especially near injector

5th US Comb. Meeting, Western States Comb. Inst., March 25-28, 2007



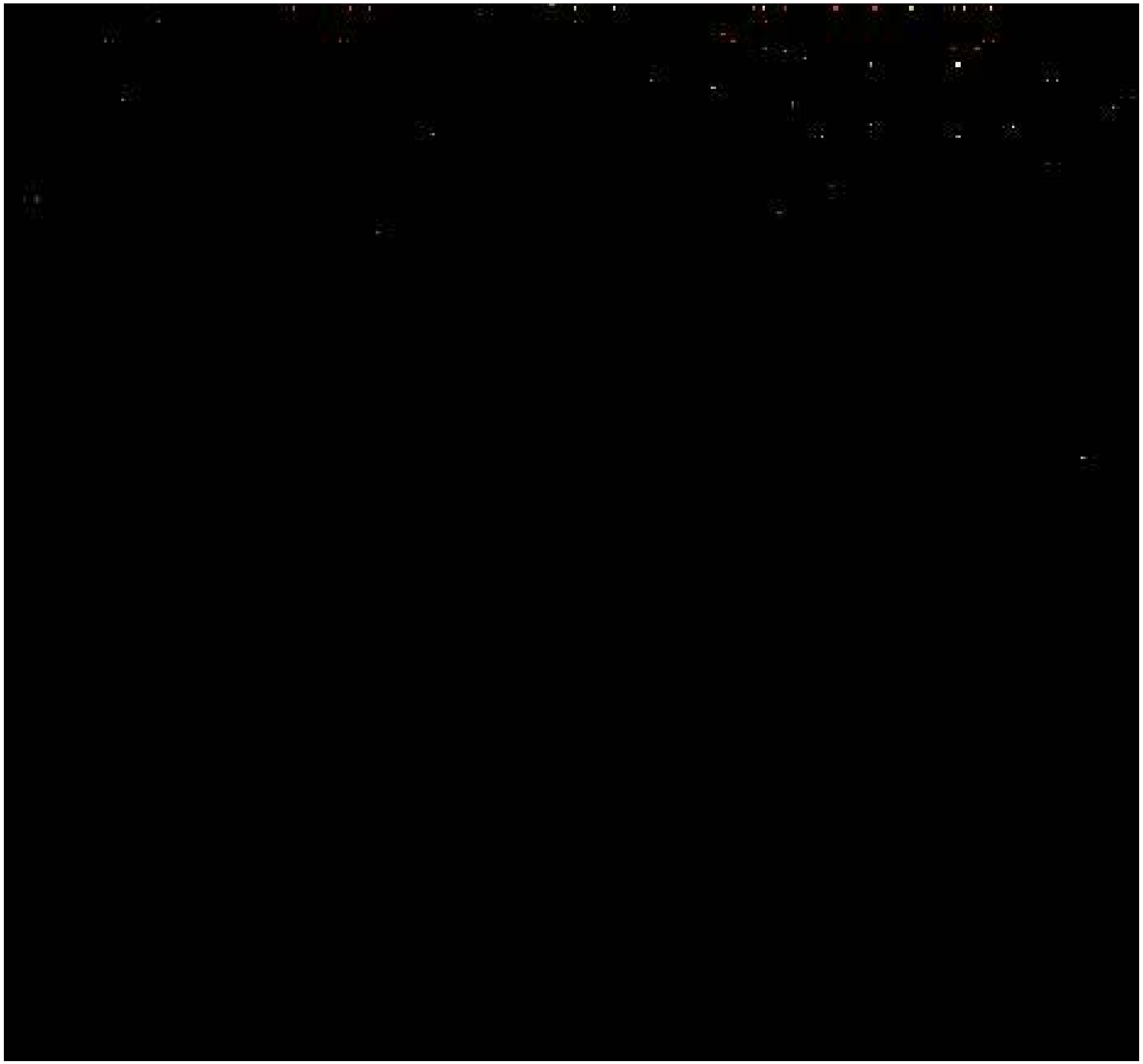
Conventional diesel: high-speed soot luminosity movie shows soot-filled jet

O_2	= 21% (no EGR)
SOI	= 10 BTDC
P_{inj}	= 1000 Bar

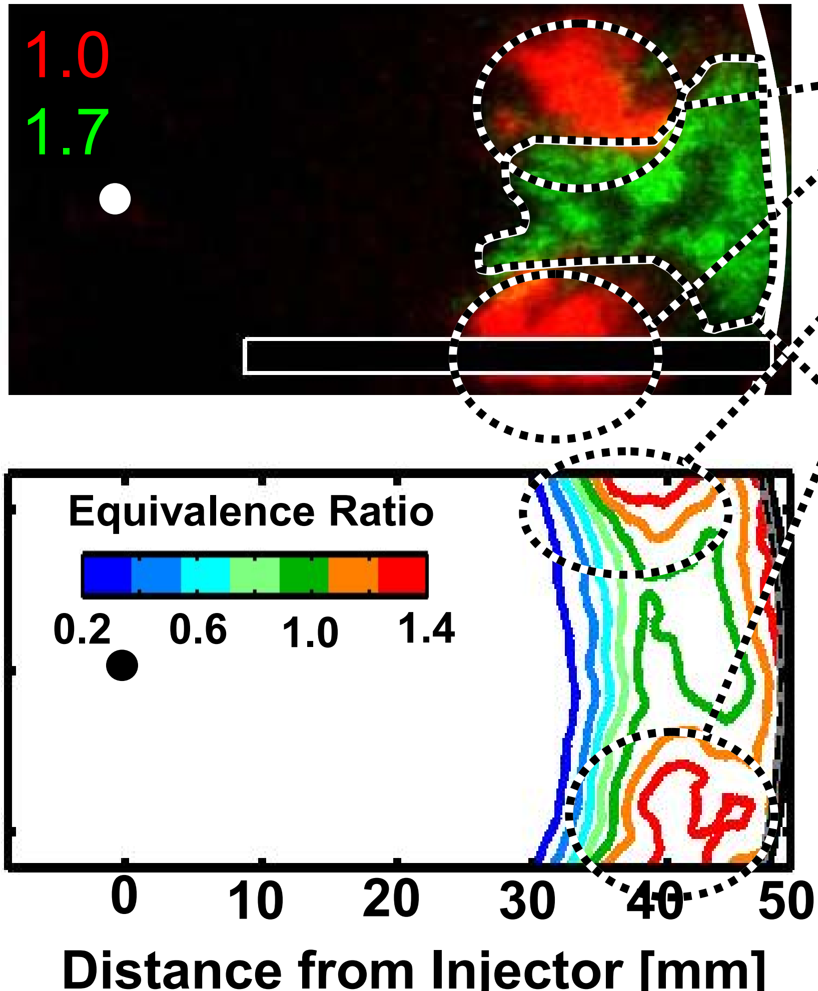


LTC diesel: soot forms mostly at head of jet, after the end of injection

O_2 = 13% (~50% EGR)
SOI = 22 BTDC
P_{inj} = 1200 Bar



Laser diag.: PAH & soot in rich jet head, OH widely distributed (likely NOx too)



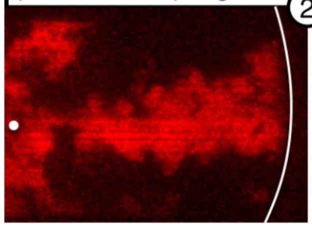
- PAH (red, top) forms at near head of jet, after the end of injection.
- Vapor fuel measurements (contours, bottom) show richest regions are at the head of the jets, especially between jets.
- OH (green, top) forms in distributed, well-mixed region between the soot (no thin flame)
- NO likely forms in the same high-temperature regions as OH

(SAE 2008-01-1330, Genzale et al.)

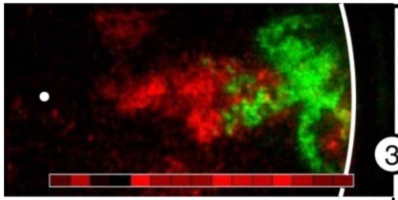
Evolving conceptual model extension: conventional & LTC diesel very different

O_2 = 13% (high EGR)
SOI = 22 BTDC
P_{inj} = 1200 Bar

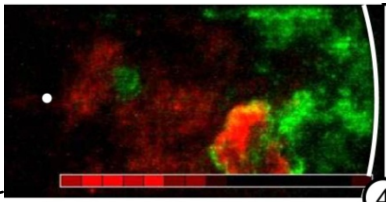
H_2CO PLIF: 1st-Stage Ignition
Formadehyde appears nearly simultaneously in the jet, from fuel-lean (upstream) to fuel-rich (downstream) regions. (2)



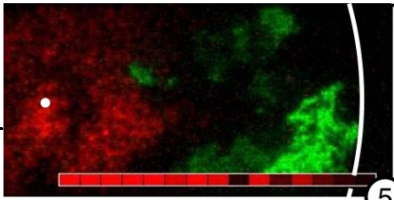
OH PLIF: 2nd-Stage Ignition
OH (green) appears downstream, in wide bands distributed over the width of the jet. Formaldehyde (red) remains upstream. (3)

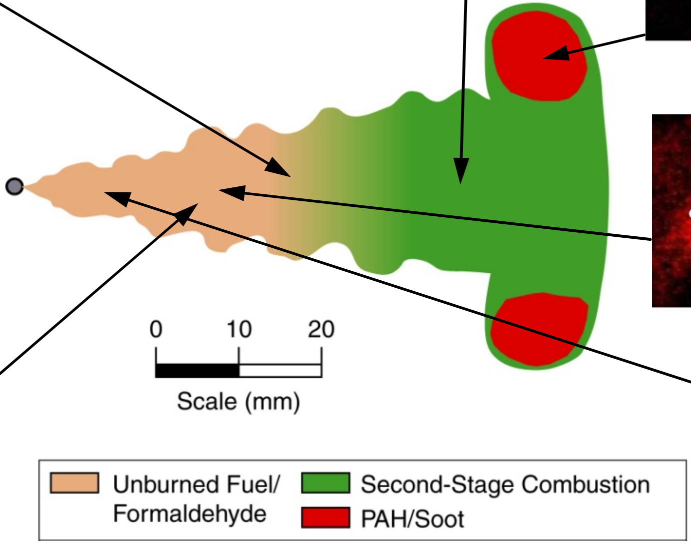


PAH PLIF: Soot Precursors
PAH species (bright red) form near the jet head-vortex, where adjacent jets interact. Formaldehyde (dim red) still remains, upstream. (4)

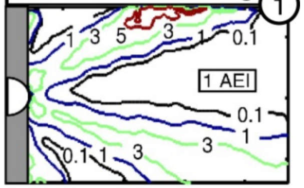


H_2CO PLIF: Unburned HCs
Late in the cycle, formaldehyde (red) indicates unburned hydrocarbons near the injector. OH (green) indicates combustion is more complete downstream. (5)





Fuel-Tracer PLIF: Φ
After fuel injection, equivalence ratios decrease and liquid fuel vaporizes rapidly due to faster mixing. (1)



Fuel-Tracer PLIF: Φ
During ignition delay, near-injector mixtures become too fuel-lean to burn completely, leading to unburned HCs. (6)