Direct-Injection CNG
Combustion Research in a Heavy-Duty Optical Engine

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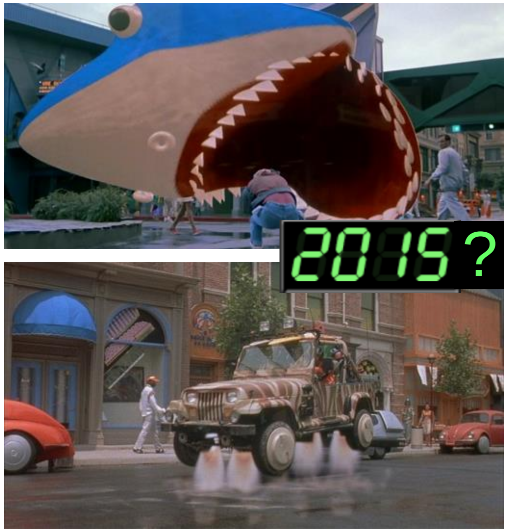
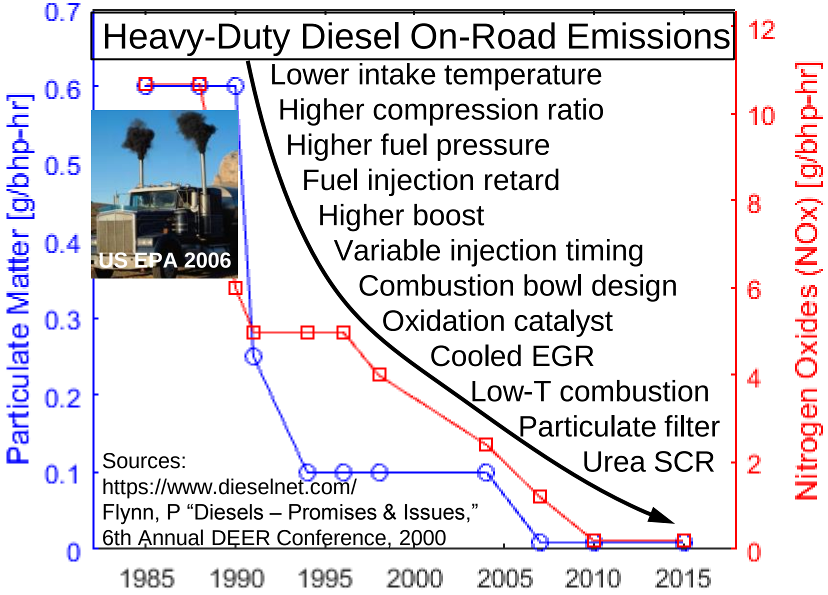
***"Back to the Future Day"* – October 21, 2015**



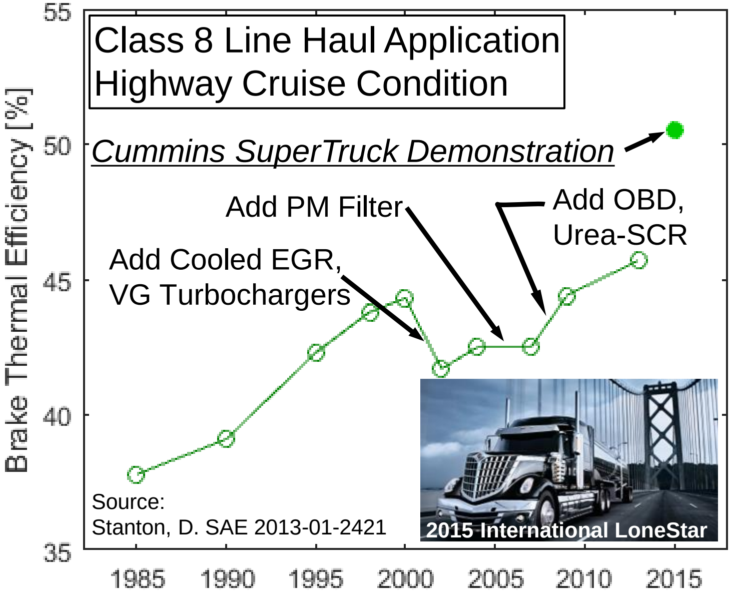
Sponsor: USDOE Office of FreedomCAR and Vehicle Technologies
Program Managers: Gurpreet Singh, Leo Breton, Kevin Stork

1985-2015: Heavy-duty diesel emissions decreased over 50-fold, efficiency up by 8(13) percentage pts.

- Because of its overall fuel-lean charge (λ>1.4 or ϕ<0.7), a conventional diesel engine cannot use the 3-way catalyst for exhaust aftertreatement that has worked well for stoichiometric gasoline (& CNG) engines since 1981
  - Needed to find in-cylinder solutions as emissions targets were tightened through 2004, then add aftertreatment in 2007/2010 (PM filter + Urea SCR)
- Some emissions reduction technologies also brought fuel efficiency improvements
  - DOE SuperTruck 2015 goal/demonstration: 50+% BTE; was <38% in 1985



Sources:
https://www.dieselnet.com/
Flynn, P "Diesels – Promises & Issues," 6th Annual DEER Conference, 2000

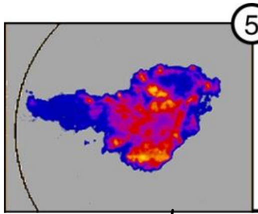


Source:
Stanton, D. SAE 2013-01-2421

In-cylinder strategies to improve diesel emissions & efficiency were guided by optical diagnostics

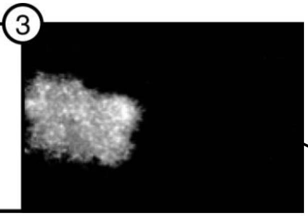
O_2 = 21% (no EGR)
SOI = 10 BTDC
P_{inj} = 1000 Bar

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

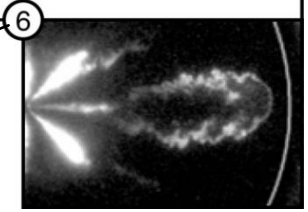


LII: Soot Concentration
Shortly after the premixed fuel burns, soot is formed in the hot, fuel-rich region throughout the jet cross-section.

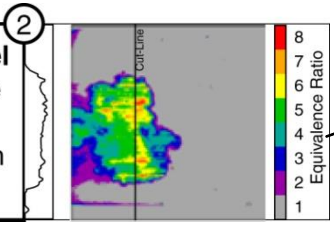
Chemiluminescence: Ignition
Spontaneous ignition reactions occur in the hot mixture of fuel and air throughout the leading portions of the jet.

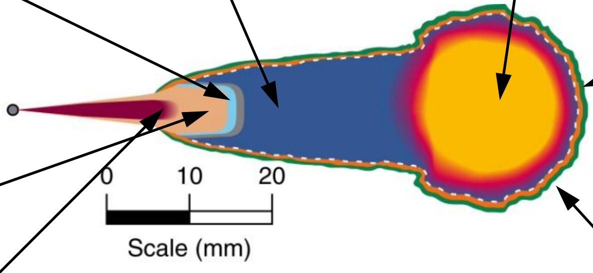


OH PLIF: Diffusion Flame
Shortly after the premixed fuel burns, a thin diffusion flame forms on the jet periphery, surrounding the interior soot cloud.

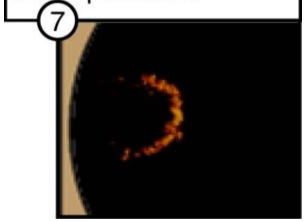


Rayleigh Scatter: Vapor Fuel
The vaporized fuel-air mixture downstream of the liquid is relatively uniform and fuel-rich (Φ = 2-4).

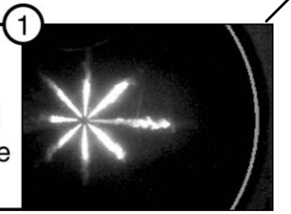




NO PLIF: Thermal NO
NO forms on the periphery of the jet in the hot diffusion-flame products.



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



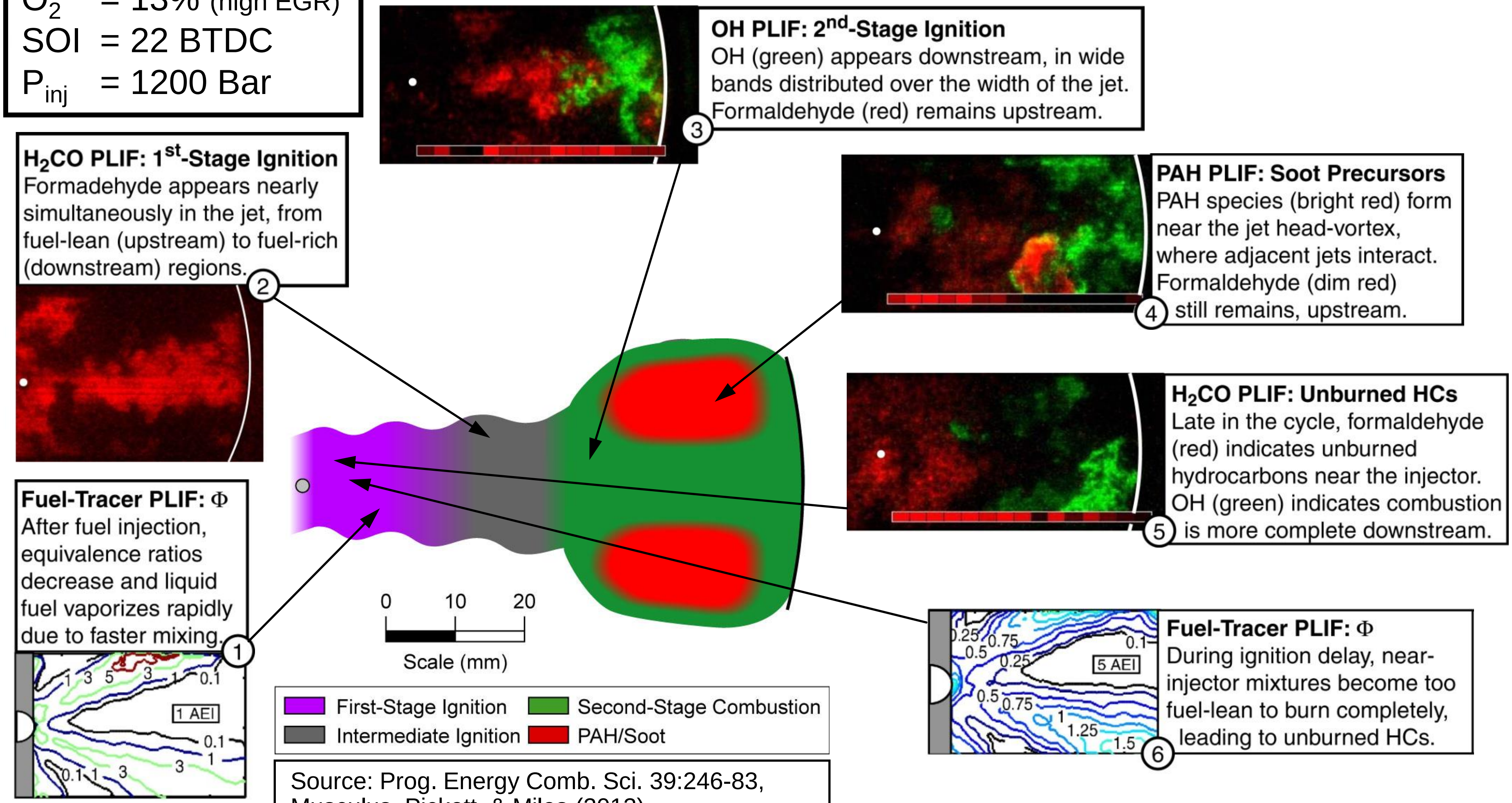
🟥 Liquid Fuel	🟦 Fuel-Rich Premixed Flame
🟧 Rich Vapor-Fuel/Air Mixture	⬛ Initial Soot Formation
🟧 Diffusion Flame	🟩 Thermal NO Production Zone
	▨ Soot Oxidation Zone

Low ▬ High
Soot Concentration

Source: SAE 970873, Dec (1997)

NG studies would need different optical tools. Example: Low-temperature diesel combustion

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



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

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

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

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

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.

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

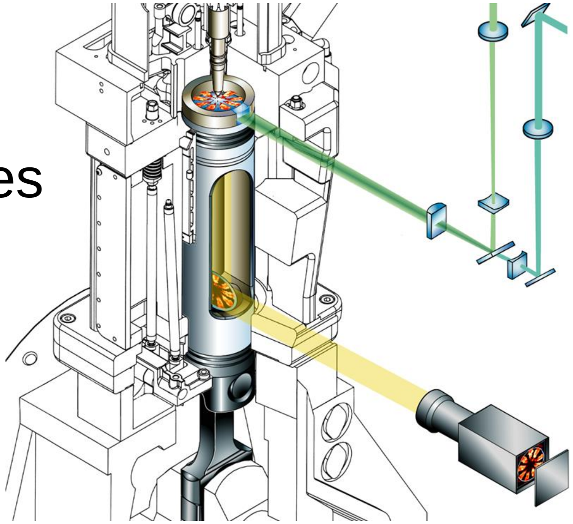
🟪	First-Stage Ignition	🟩	Second-Stage Combustion
⬛	Intermediate Ignition	🟥	PAH/Soot

Source: Prog. Energy Comb. Sci. 39:246-83, Musculus, Pickett, & Miles (2013)

Improvements are needed at many steps in US NG supply/use chain – Sandia/CRF focus is combustion

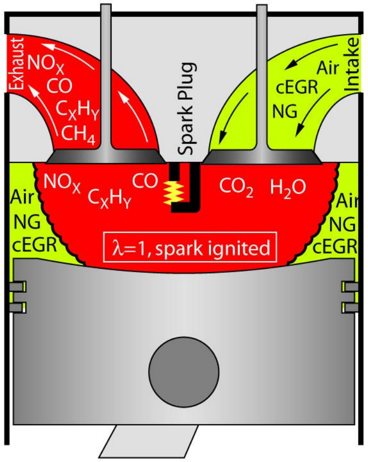
- Key NG R&D areas:
  - Distribution/refueling
  - GTL/LNG production
  - On-board storage
  - **Vehicle end-use: combustion**
- NG optical research is dwarfed by diesel studies:
  - “Optical” + “diesel” SAE papers, 1947-2015: **795**
  - “Optical” + “natural gas” SAE papers, 1992-2015: **45**
- Four NG engine combustion strategies in production:
  - “Best” combustion strategy depends on economics/regulations/performance
  - Each faces unique in-cylinder challenges

Common-platform optical engine capable of 4+ operating strategies to provide missing in-cylinder NG combustion science-base



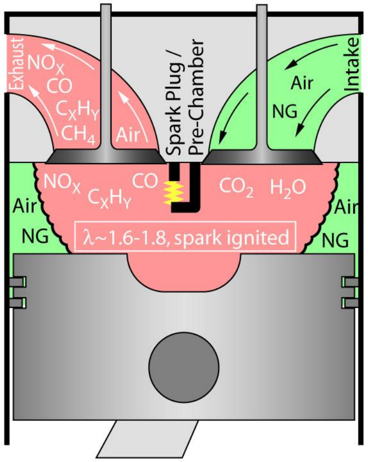
Four production NG combustion strategies today; balance of economics, regulation, & performance

Spark/Prechamber Ignition



Stoichiometric Spark Ignition

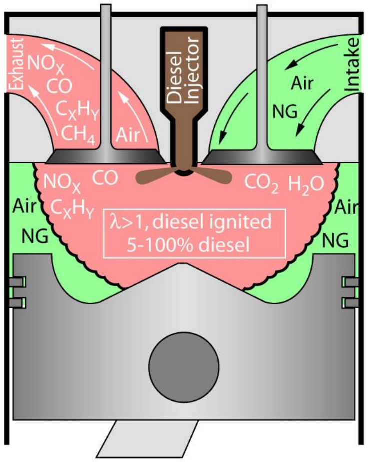
- Port/DI, premixed, cooled EGR
- 3-way catalyst
- ~36% efficiency
- 100% NG
- Cummins, Scania, Waukesha, IVECO



Lean Premixed Spark Ignition

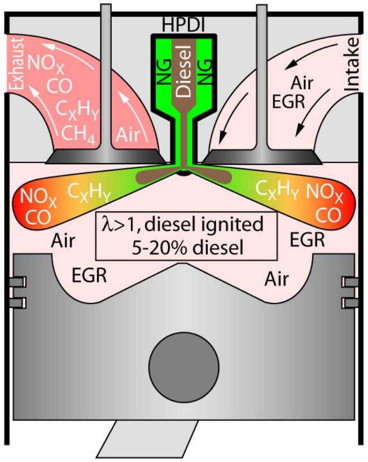
- Port/DI, premixed or stratified, EGR
- Oxy-catalyst
- ~43% efficiency
- 100% NG
- Cummins, MAN, Doosan, GE

Diesel-Pilot Ignition



Lean Premixed Diesel Pilot

- Port/DI, premixed or stratified, cEGR
- Oxy-catalyst
- ~45% efficiency
- 0-95% NG
- Volvo (Hardstaff, G-Volution retro.)

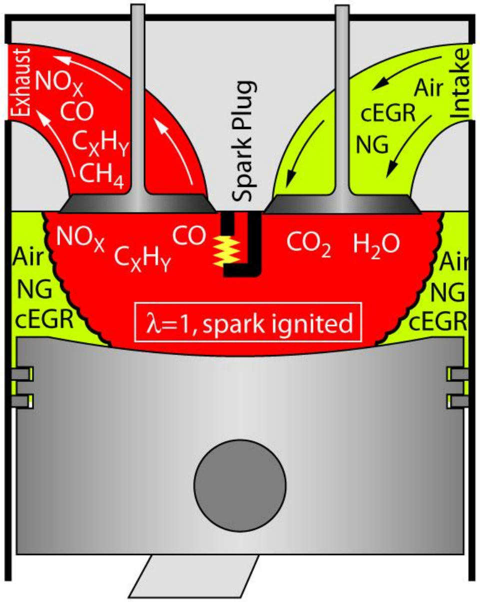


Direct Injection Diesel Pilot

- DI stratified/jets NG+diesel, EGR
- Catalyzed DPF, Urea SCR
- ~46% efficiency
- ~90% NG
- Westport, Volvo

Each NG strategies faces unique combustion challenges

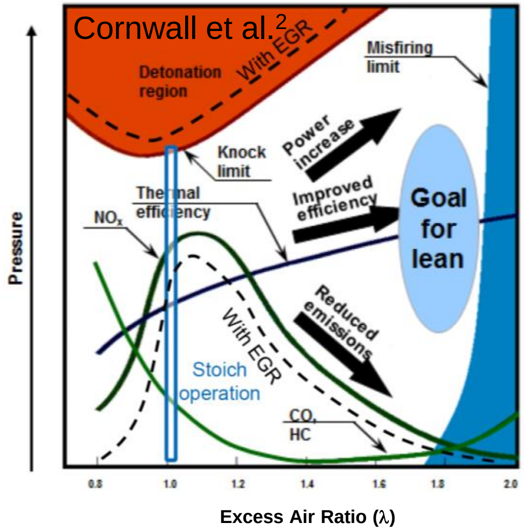
Stoichiometric spark-ignition challenges include efficiency, fuel variability, and knock/load limits



Intake	Premixed NG, Stoichiometric	Methane-specific 3-way catalyst for CO, HC, NOx[2]
	Cooled EGR	Reduces NOx & heat load, raises knock limit[1,2]
Fuel Efficiency	~36%[1]	Throttle, Timing Retard, EGR + low compression ratio to avoid knock[1]
NG Fraction	100%[1,2]	No diesel fall-back[2]
Key HD Dev.	Cummins, Scania, Waukesha, IVECO[2]	

In-cylinder gaps for NG stoichiometric/EGR spark ignition

- Controlling flame kernel/growth/knock transition[1]
  - Surface/geometry effects
  - Fuel composition effects
  - EGR/fuel mixing/distribution effects[1]
- Using turbulence to increase flame speed with EGR
  - Effects on ignition, misfiring issues[1]


Cornwall et al.[2]

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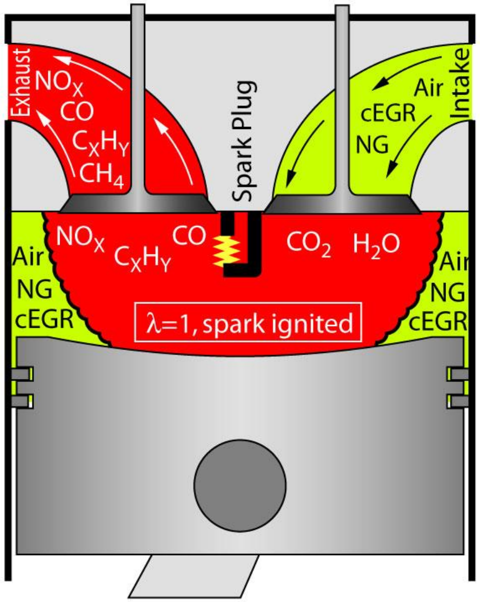
[1] MTZ Worldwide 75(10):1-15, Figer, Seitz, Graf, Schreier (2014)

[2] IMechE S1807, Cornwall, Foster, Noble (2014)

Stoichiometric spark-ignition challenges include efficiency, fuel variability, and knock/load limits



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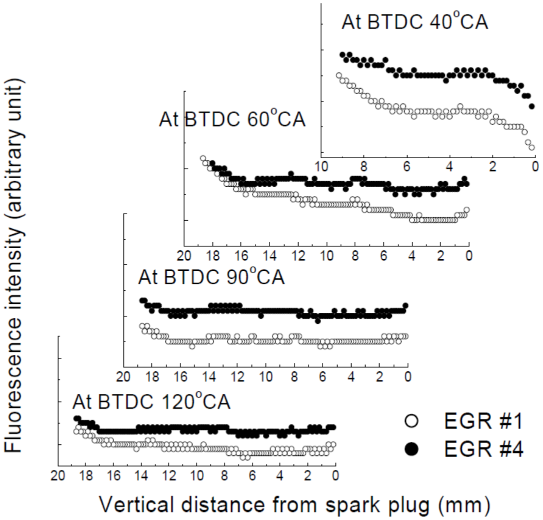
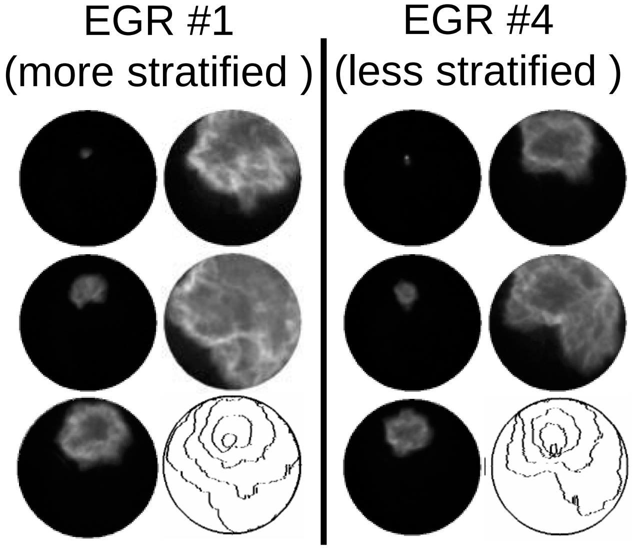
Key HD Dev.	Cummins, Scania, Waukesha, IVECO[2]	

<u>Previous optical work[3]:</u>

- With LPG, intake port valve can place EGR in bottom of cylinder
- More stratified EGR burns faster and with higher efficiency




EGR #1 (more stratified)

EGR #4 (less stratified)

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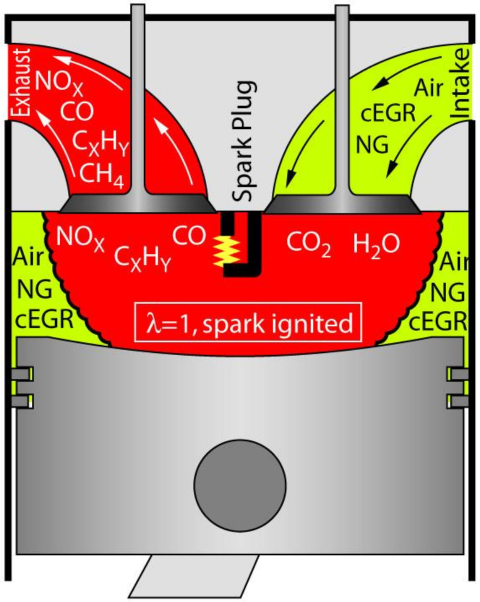
[1] MTZ Worldwide 75(10):1-15, Figer, Seitz, Graf, Schreier (2014)

[2] IMechE S1807, Cornwall et al., (2014)

[3] SAE 2004-01-0928, Woo et al. (2004)

Stoichiometric spark-ignition challenges include efficiency, fuel variability, and knock/load limits



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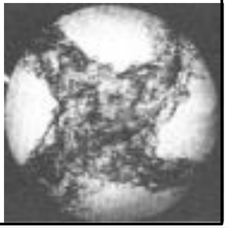
Understand factors that control NG knock with EGR

- Kernel/flame growth
- Surfaces/geometry
- Fuel composition (inc. H_2)
- EGR distribution

Schlieren images of knocking combustion[3]

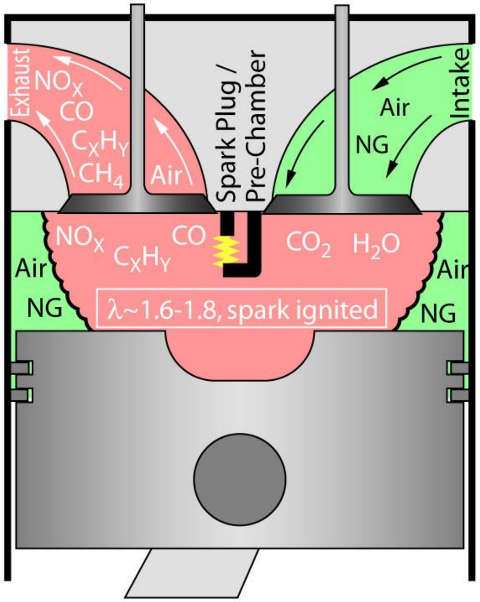
Prior to autoignition of end-gas

Onset of knocking



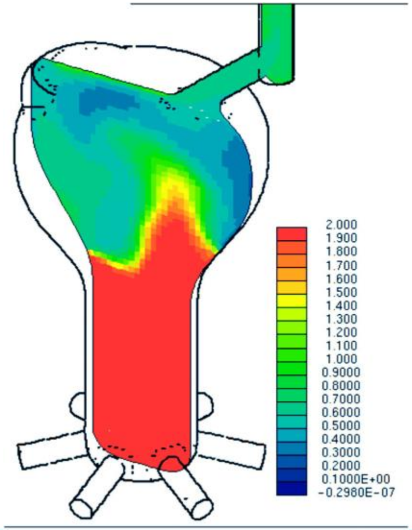
[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] Proc. Comb. Inst. 20, Smith et al. (1984)
[4] www.sandia.gov/ecn/tutorials/visualization.php

Lean premixed spark-ignition challenges include ignition stability, transients, and CH_4 slip

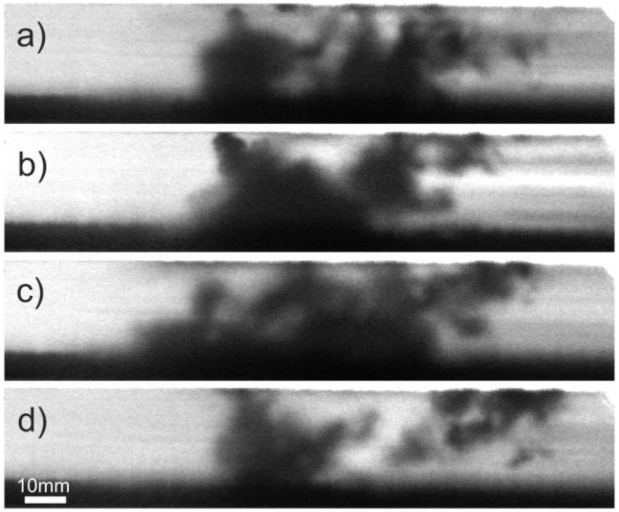


Intake	Lean-premixed NG (λ~1.6-1.8)[1]	Aftertreatment for HC and CO, possibly NOx
Efficiency	~43%[1]	high specific heat ratio, high compression ratio[1,2]
Heavy-Duty	Cummins, Scania, MAN, GE (Jenbacher)[2]	
Challenges	Ignition stability (pre-chamber), transients, SCR for US2010/Euro VI NOx, CH_4 slip (low exhaust T / catalyst-efficiency)[1,2]	

Pre-chamber simulation[3]



Acetone PLIF: fuel consumption[3]

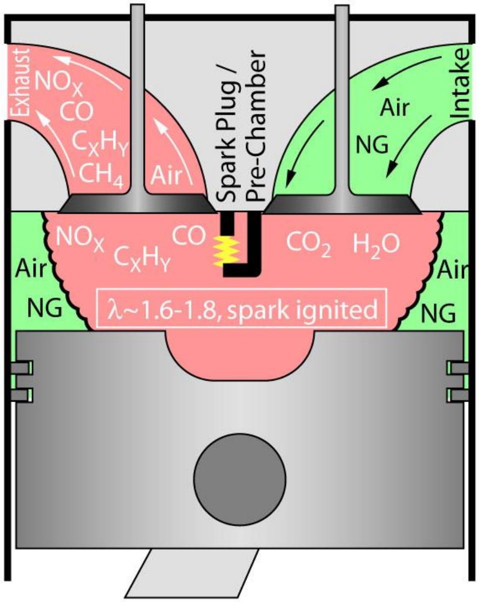


Previous optical work[3]:

- PLIF shows pre-chamber stratification, comp. inflow
  - Variability lowers knock limit
- Pre-chamber-jet mixing increases flame speed

[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] SAE 2014-01-1330, Wellander et al.

Lean premixed spark-ignition challenges include ignition stability, transients, and CH_4 slip



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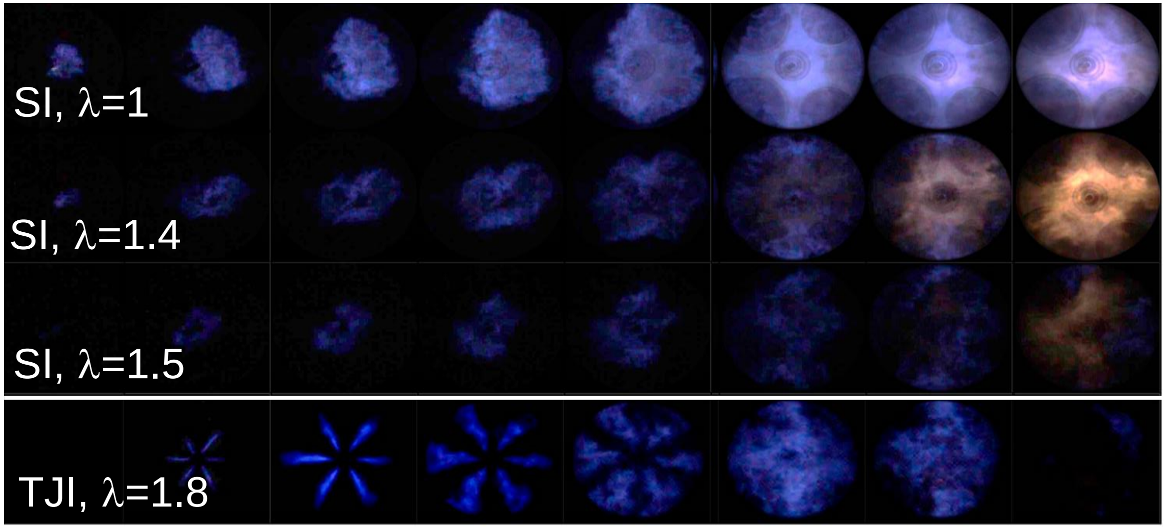
Natural Luminosity imaging[3]

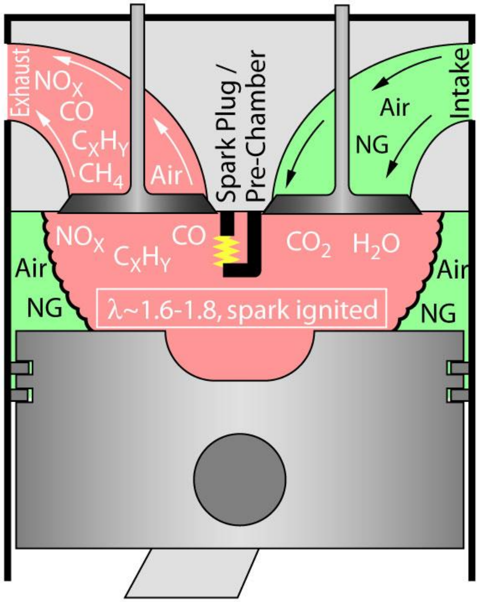


Previous optical work[3]:

- Turbulent jet ignition (TJI) pre-chamber allows leaner operation with higher stability & combustion efficiency

[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] SAE 2012-01-0823, Attard et al.

Lean premixed spark-ignition challenges include ignition stability, transients, and CH_4 slip



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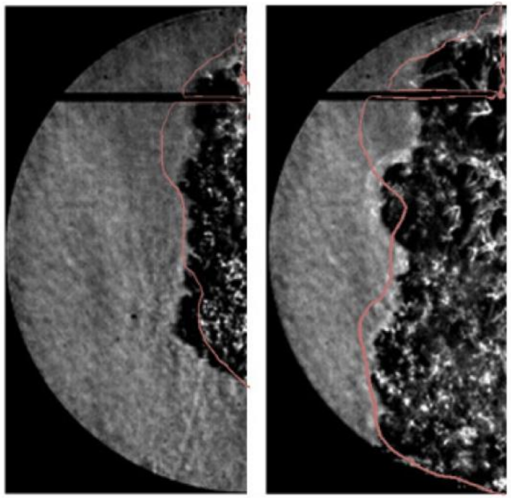
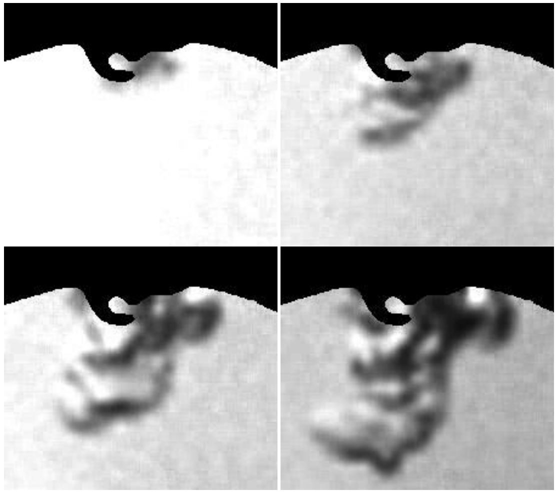
Schlieren spark-ignited jet[3]



Schlieren jet-capillary spark plug[4]

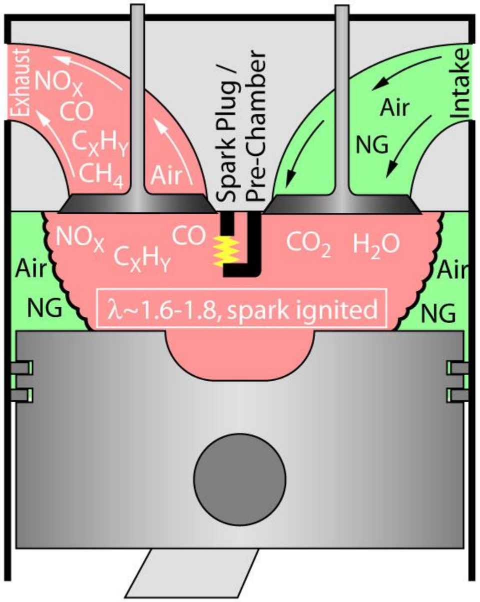


<u>Previous optical work[3,4]:</u>

- Spark-ignited jets improve combustion speed/stability at overall lean conditions

[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] SAE 2015-01-0398, Bartolucci et al.
[4] SAE 2007-01-1913, Chan et al.

Lean premixed spark-ignition challenges include ignition stability, transients, and CH_4 slip



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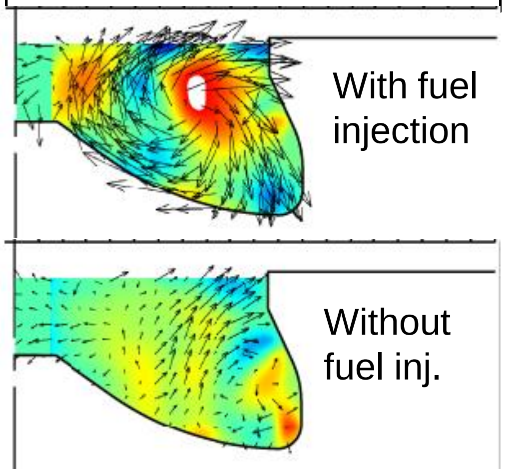
Understand fuel-lean flame ignition/propagation issues

- Flow/piston interactions[3]
- Lean spark/pre-chamber ignition kernel growth[4]
- Incomplete combustion[4]

Particle Image Velocity Measurements[3]

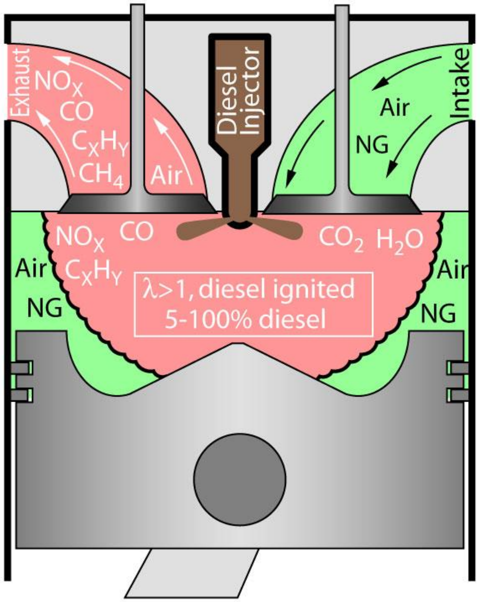


With fuel injection

Without fuel inj.

[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] DOE Annual Merit Review, Miles (2006)
[4] Ph.D Thesis, U. of Wisconsin, Kokjohn (2012)

Lean premixed diesel-pilot ignition challenges include combustion efficiency, aftertreatment cost



Intake	lean-premixed NG + EGR	aftertreatment for HC and CO, usually NOx
Efficiency	~45%[3]	high specific heat ratio, high compression ratio[1,2]
NG fraction	0-95%[1,2,3]	can run 100% diesel[1,2]
Heavy-Duty	Volvo; retrofit: CAP, Hardstaff, G-Volution[2]	
Challenges	combustion efficiency (CO, CH_4), CH_4 catalysts, NOx aftertreatment costs[1,2]	

Previous optical work[4]:

- OH Chemiluminescence shows bowl-wall ignition, incomplete combustion at center for low ϕ
- Fuel-tracer PLIF: fuel-lean at center, akin to diesel LTC PCCI

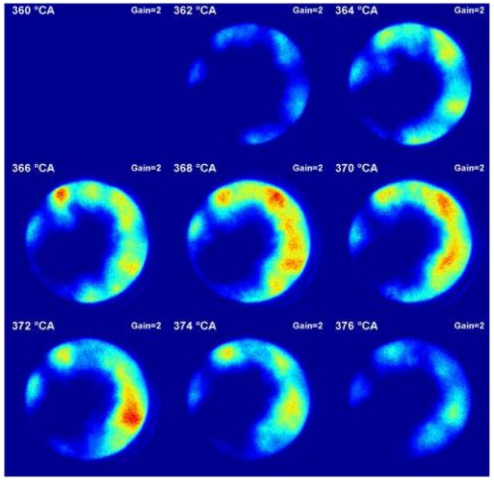
[1] MTZ Worldwide 75, Figer et al. (2014)

[2] IMechE S1807, Cornwall et al., (2014)

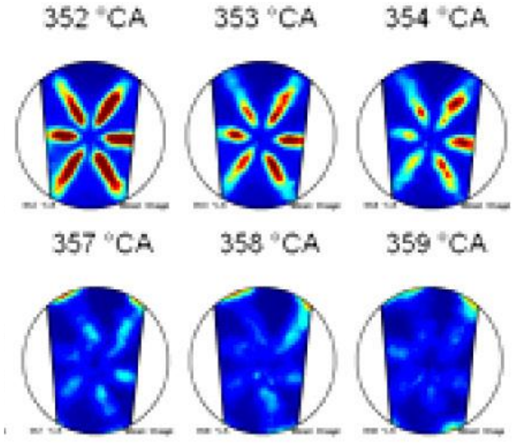
[3] SAE 2013-01-2812, Boretti et al.

[4] SAE 2014-01-1313, Dronniou et al.

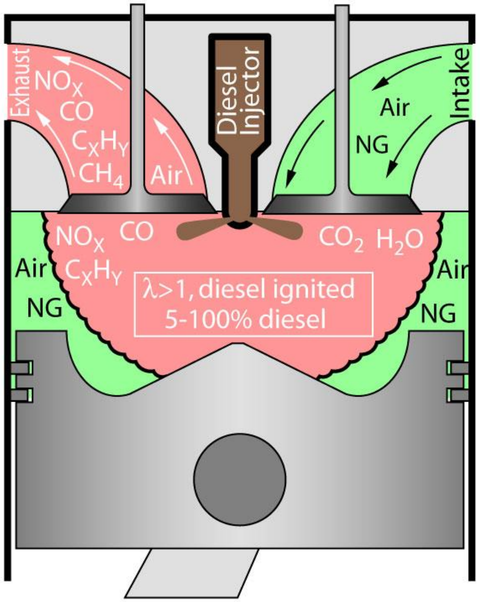
OH Chemiluminescence[4]



Fuel-tracer PLIF[4]



Lean premixed diesel-pilot ignition challenges include combustion efficiency, aftertreatment cost



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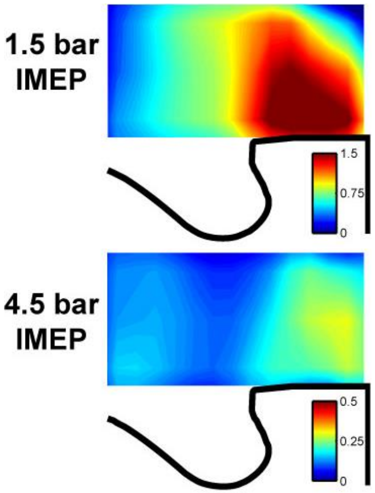
Challenges	combustion efficiency (CO, CH_4), CH_4 catalysts, NOx aftertreatment costs[1,2]	

Understand fuel-lean NG w/ diesel-pilot ignition issues

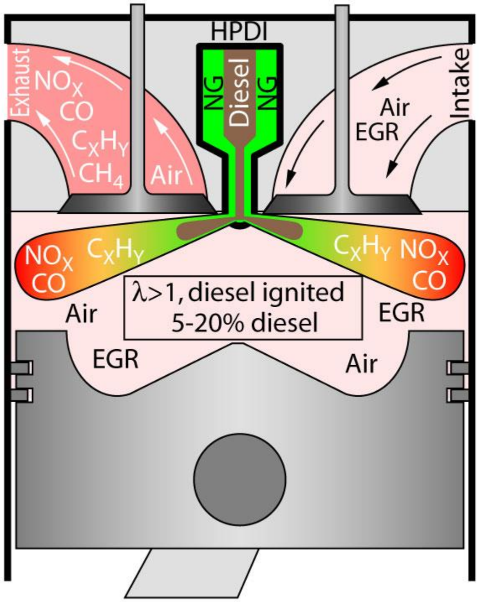
- Source of CO (lean/rich)[4]
- Incomplete combustion[5]
  - CH_4/Intermediates[5]
- Source of NO (pilot comb.)

[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] SAE 2013-01-2812, Boretti et al.
[4] DOE Annual Merit Review Presentation, Miles, (2010)
[5] Ph.D Thesis, U. of Wisconsin, Kokjohn (2012)

CO Fluorescence Images[4]

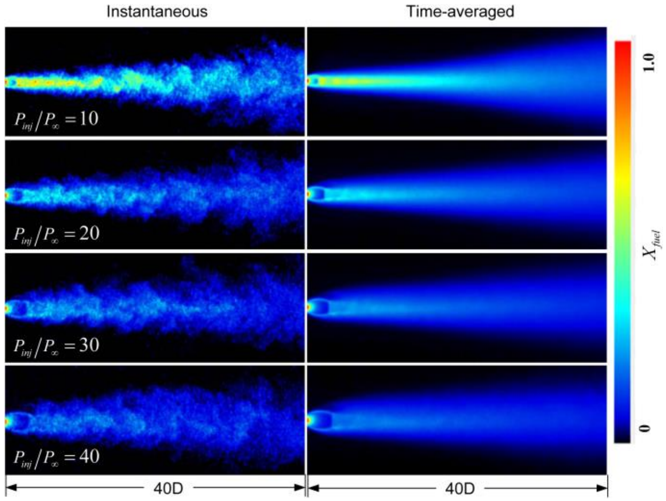


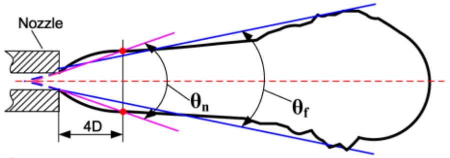
High-pressure direct injection challenges include diesel aftertreatment cost, injection interactions

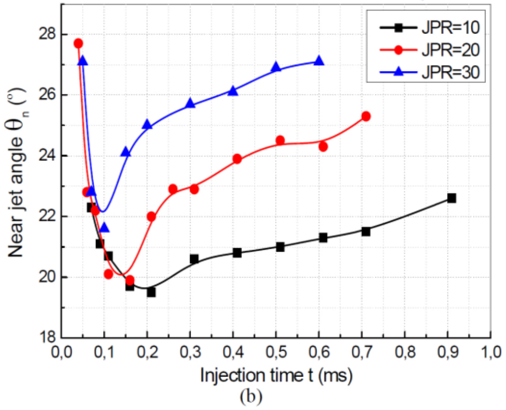


Intake	air + EGR	DPF + Urea SCR (diesel)
Efficiency	~46%[1,3]	high specific heat ratio, high compression ratio[1,2]
NG fraction	~90%[2]	can't run 100% diesel[2]
Heavy-Duty	Volvo; retrofit: CAP, Hardstaff, G-Volution[2]	
Challenges	Diesel-like emissions, optimize dual inj.[1,2]	

Acetone PLIF: N_2 jet in chamber[4]





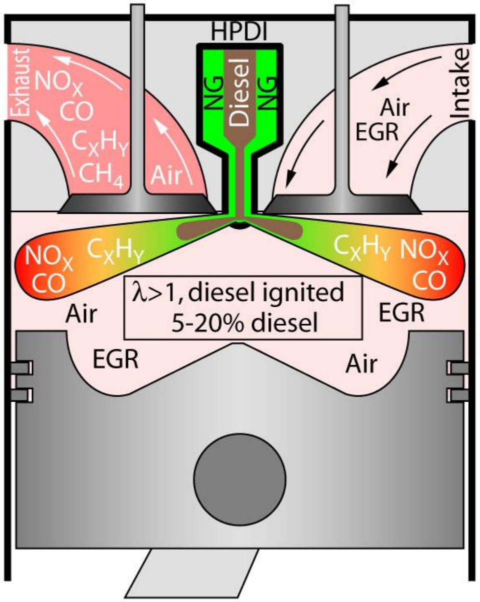


Previous optical work[4]:

- PLIF shows pressure ratio affects shock structures
- PR also affects spreading angle, shock-induced turbulence aids mixing

[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] SAE 2013-01-2421, Stanton
[4] SAE 2014-01-1619, Yu et al.

High-pressure direct injection challenges include diesel aftertreatment cost, injection interactions



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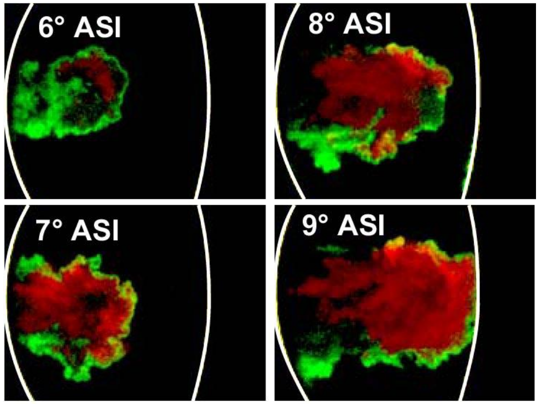
Understand high-pressure direct-injection NG issues

- Flame lift-off with NG and diesel pilot ignition[4]
  - OH LIF/chemiluminesc.
  - Soot LII / PAH LIF
- Explore LTC/premixing[5]

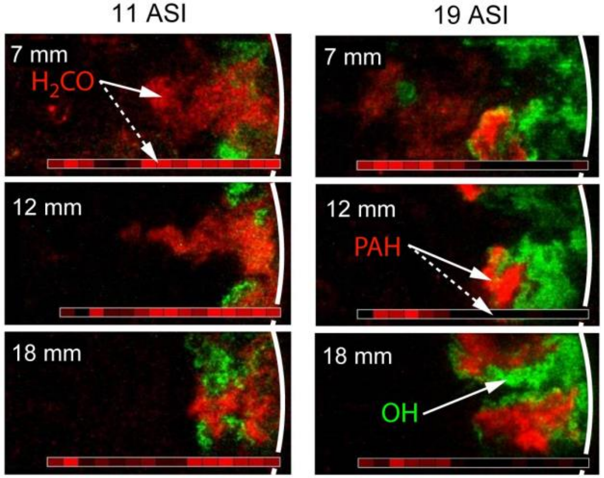
[1] MTZ Worldwide 75, Figer et al. (2014)
[2] IMechE S1807, Cornwall et al., (2014)
[3] SAE 2013-01-2421, Stanton

Diesel: combined soot PLII (red) and OH PLIF (green)[4]



[4] SAE 2001-01-1295, Dec & Tree

Diesel LTC: combined HCO/PAH PLIF (red) and OH PLIF (green)[5]



[5] SAE 2009-01-2699, Genzale et al.

Sandia/CRF plan: convert HD optical diesel engine for NG – common platform, 4(+) comb. strategies

Three NG fuel delivery systems

1. Up to 10 bar intake-port injector
2. Up to 100 bar side-wall DI
3. Up to 600 bar Westport HPDI-style combined NG + diesel

Three ignition systems

1. Conventional spark plug
2. Diesel pilot ignition
3. Pre-chamber/spark system

Fueled with scientific-grade NG

- Certified mix with H_2 and/or C_2-C_4 species; NG recovery system

Common-platform optical engine can provide the missing science base for multiple NG strategies in reciprocating HD engines