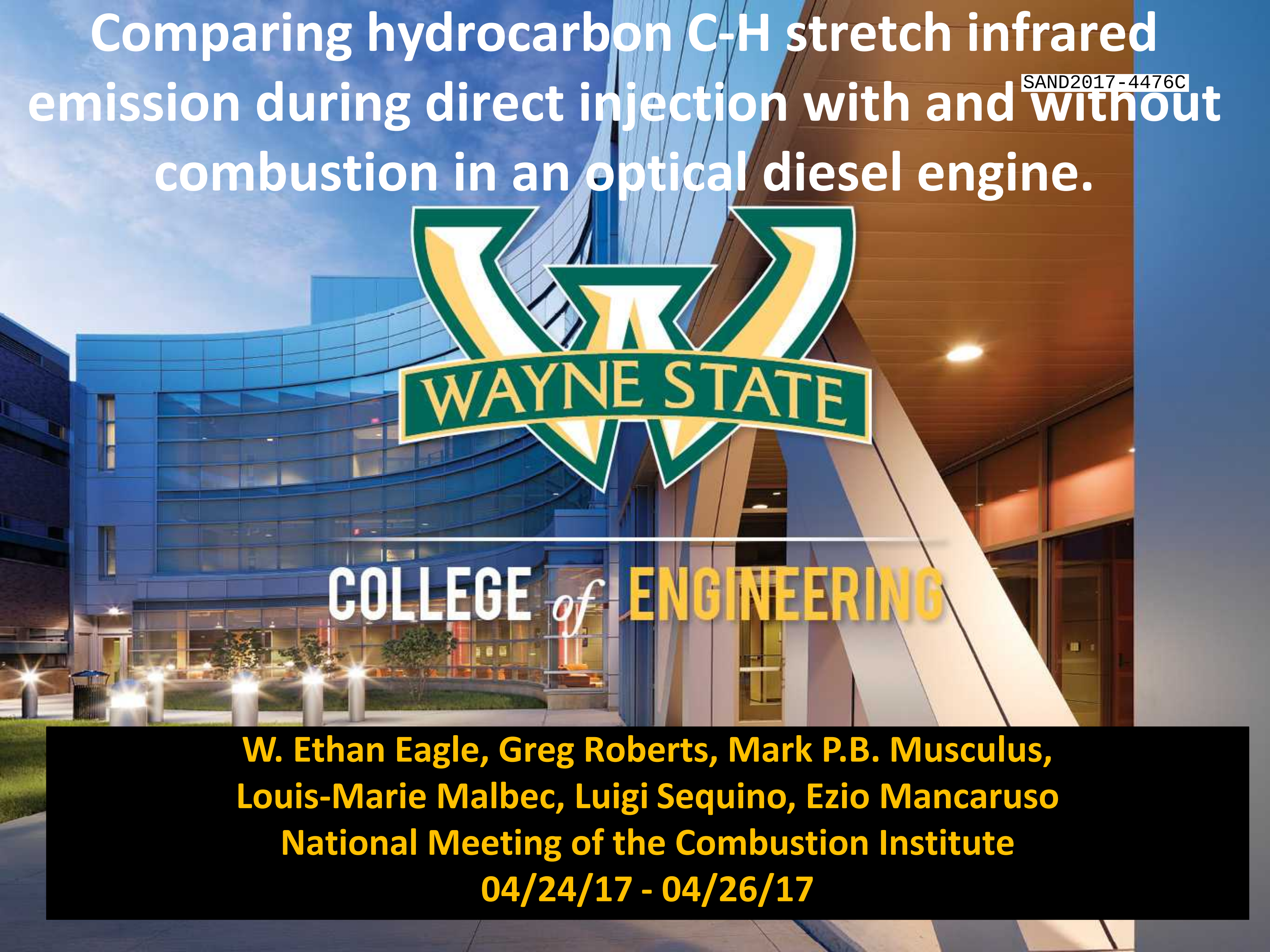

Comparing hydrocarbon C-H stretch infrared emission during direct injection with and without combustion in an optical diesel engine.

SAND2017-4476C

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W. Ethan Eagle, Greg Roberts, Mark P.B. Musculus,
Louis-Marie Malbec, Luigi Sequino, Ezio Mancaruso

National Meeting of the Combustion Institute
04/24/17 - 04/26/17

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- Wayne State University
- Istituto Motori
- IFPEN
- Sandia National Labs, CRF

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Opportunity is waiting for you in Detroit

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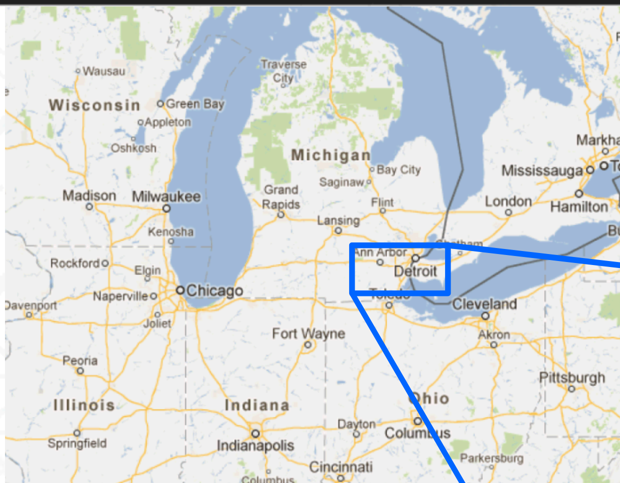
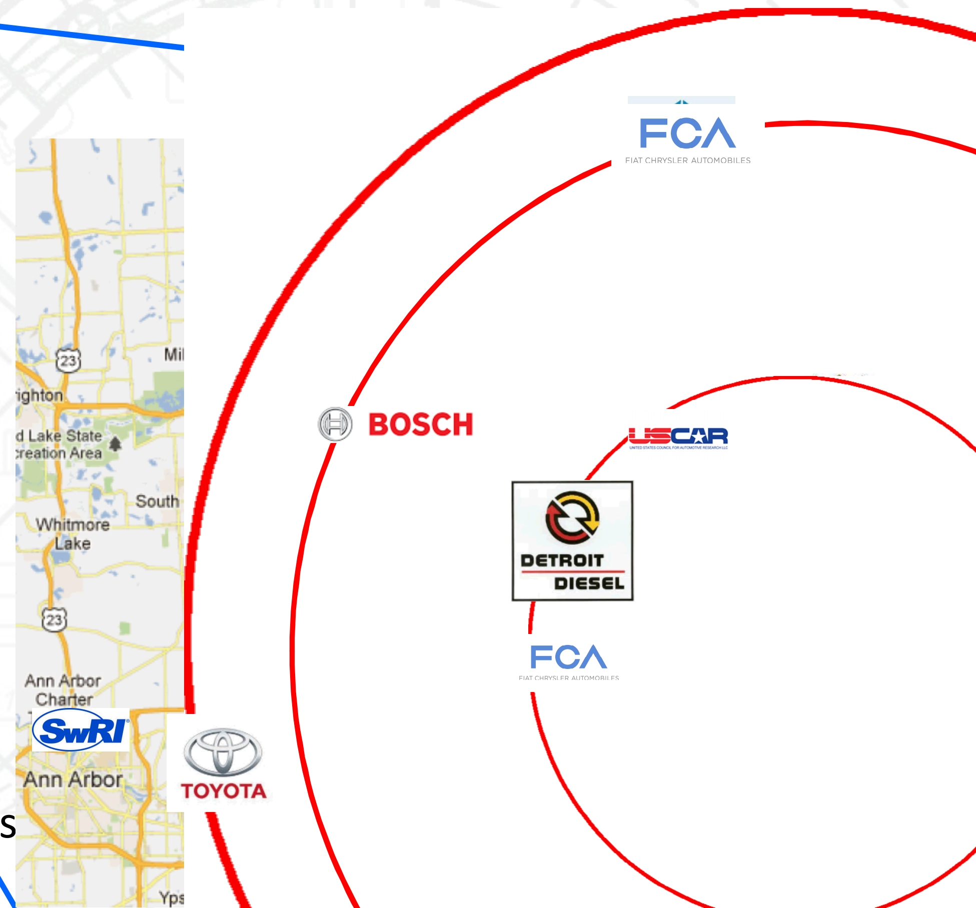


GM World Headquarters, Detroit, 3.5miles
Ford World Headquarters, Dearborn, 8.9 miles
FCA Powertrain Division, Redford, 12.4 miles
USCAR office, Southfield, 13.9 miles
Detroit Diesel, Dearborn Heights, 13.8 miles
US Army TACOM, Warren 15.5 miles
FCA US, Auburn Hills, 16.9 miles
Robert Bosch LLC, Novi, 26.9 miles
Toyota Technical Center, Ann Arbor 36.6 miles
SWRI Ann Arbor Tech Center, Ann Arbor, 37 miles



Objectives of this Presentation

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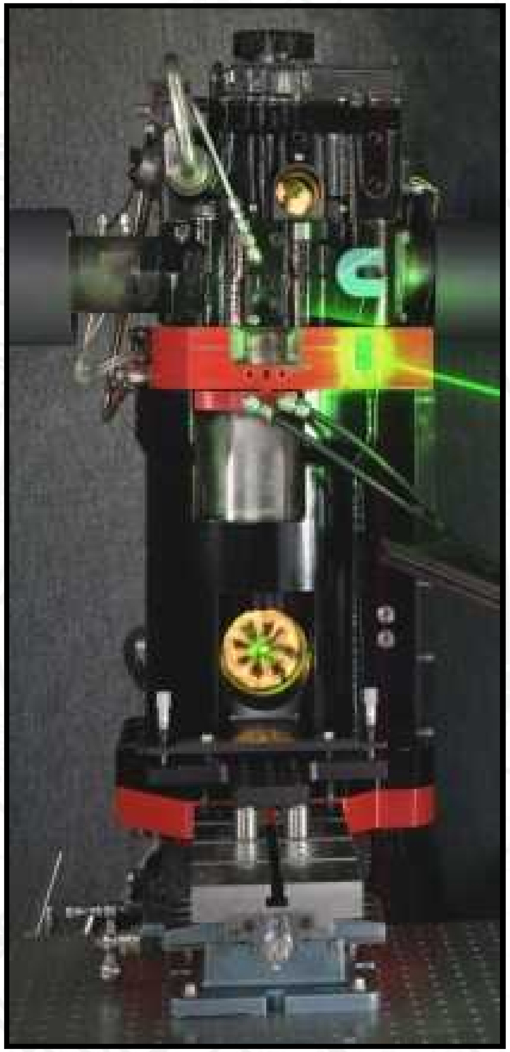
- What is the problem (or problems)?
  - Air pollution contributions from vehicles
- What is the means of attack?
  - Regulation
  - Optical Combustion Diagnostics
- Why Infrared?
  - What could we find?
  - Did we find what we were looking for?
  - How can we be sure?
- What’s next?



Sandia 2.34 L Optical Engine

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Vehicle Emissions harm health

UCLA academics exposed mice to smog and found that breathing emissions can turn the good cholesterol (HDL) into bad (LDL).

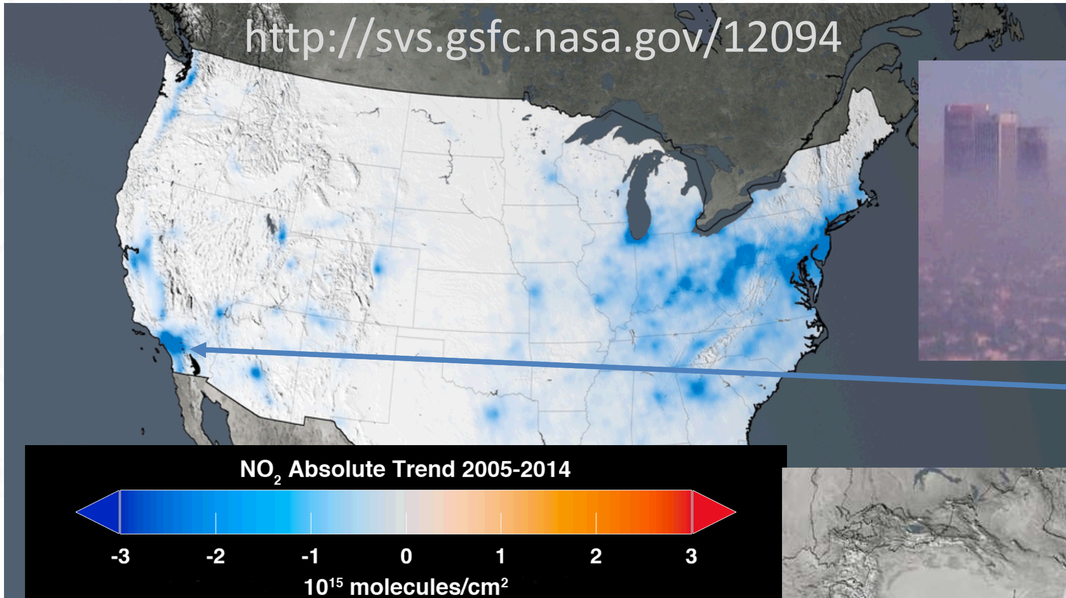
… after two weeks of exposure to vehicle emissions, mice showed oxidative damage in the blood and liver -- damage that was not reversed after a subsequent week of receiving filtered air. Altered HDL cholesterol may play a key role in this damaging process, they said. The mice exposed to emissions for two weeks "had a much-decreased ability to protect against oxidation and inflammation induced by low-density lipoprotein (LDL) cholesterol… **We suggest that people try to limit their exposure to air pollutants."**

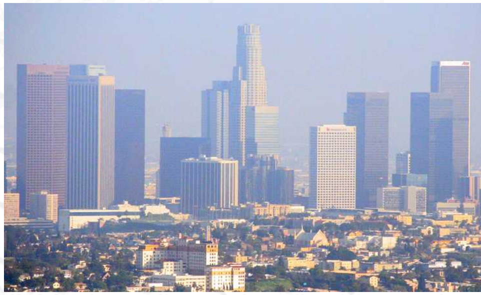
Image: Los Angeles (1980)

(2013) *Arteriosclerosis, Thrombosis and Vascular Biology*

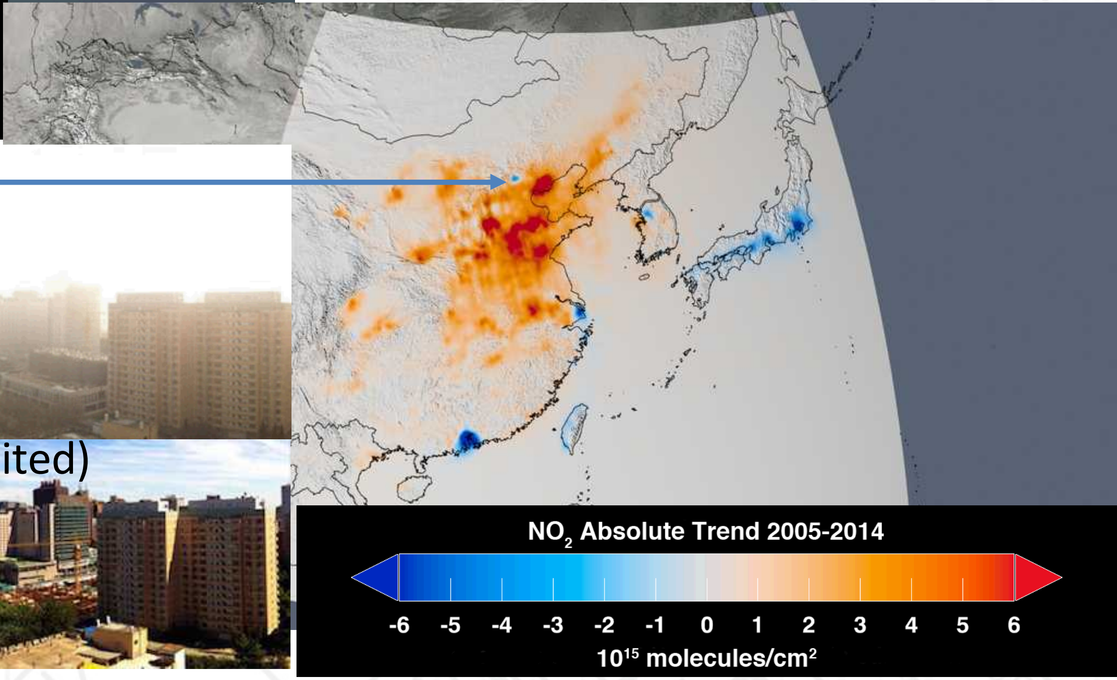
Other problems include: fuel stock sustainability, transportation infrastructure optimization, engine/fuel co-optimization, …

Measuring Impacts





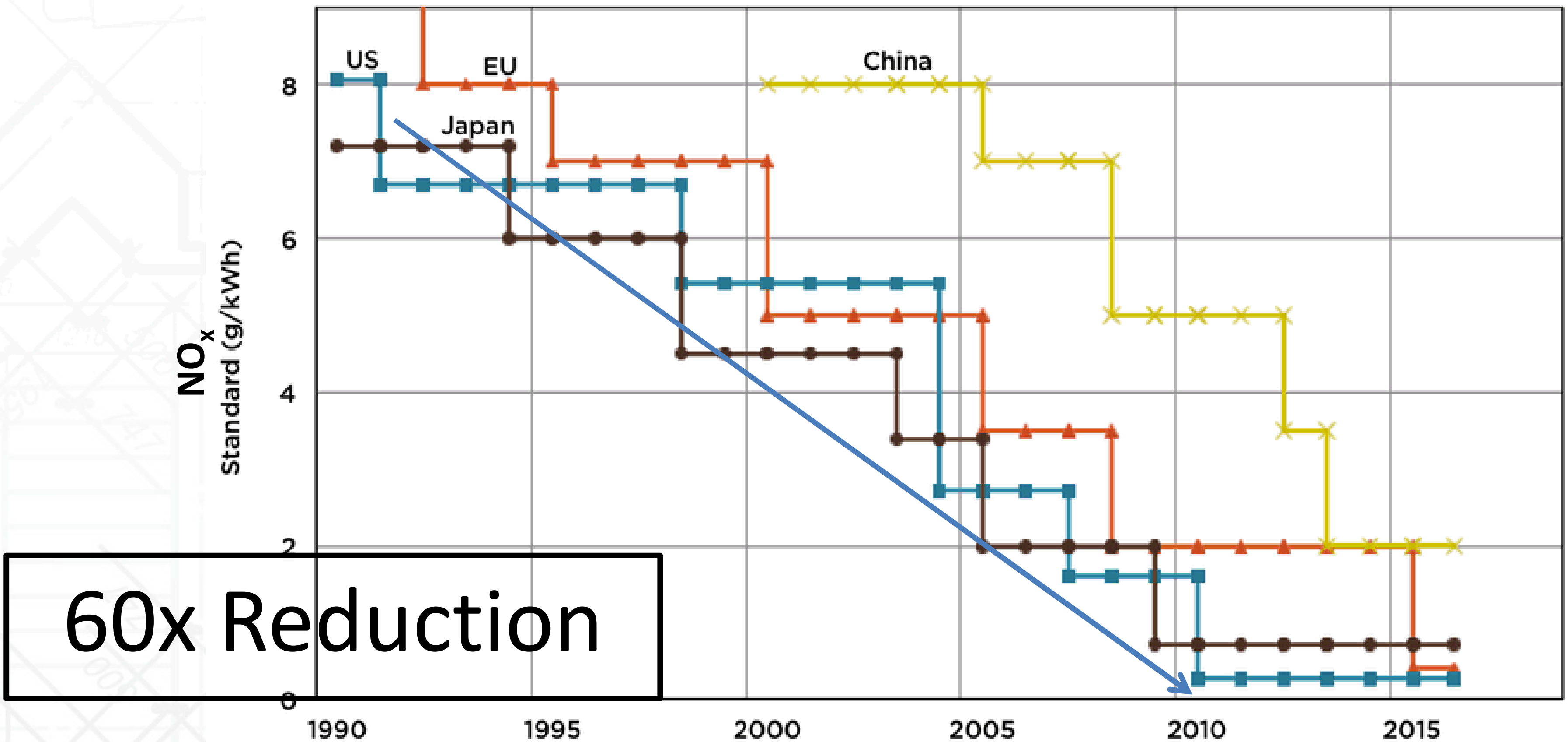
Los Angeles (1980 to 2015)



Beijing (typical)

Beijing (two weeks of driving prohibited)

Vehicle Emissions Regulation



http://transportpolicy.net/index.php?title=File:NOx_and_PM_standards_for_heavy-duty_engines.png

"It seems unlikely that the internal combustion engine will be legislated out of existence, but the quality of the engineering research required to meet the ever more stringent legislation, while delivering a competitive product is very high indeed." -Nick Collings

http://www-g.eng.cam.ac.uk/mmg/environmental/collings.html

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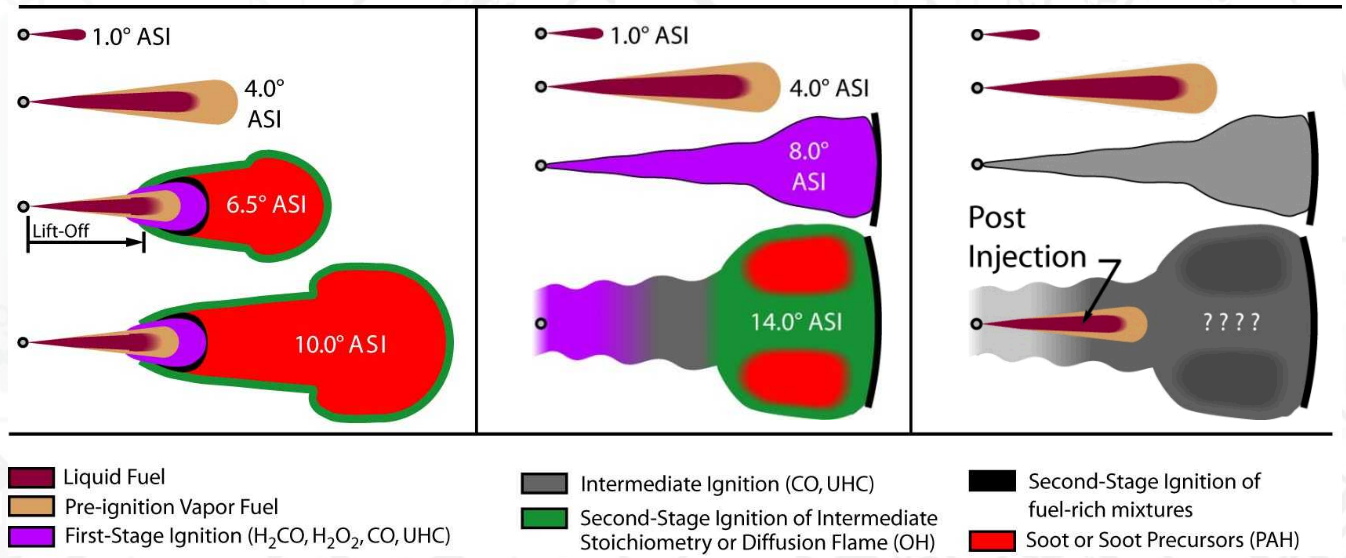
Investigate where/why pollution is created?

Develop the science to explain in-cylinder spray, combustion, and pollutant-formation processes for both conventional diesel and LTC that industry needs to design and build cleaner, more efficient engines

1997: **Conventional Diesel** (Single Injection) | 2012: **LTC Diesel** (Single Injection) | 2013+: **Multiple Injection** (Conventional & LTC)



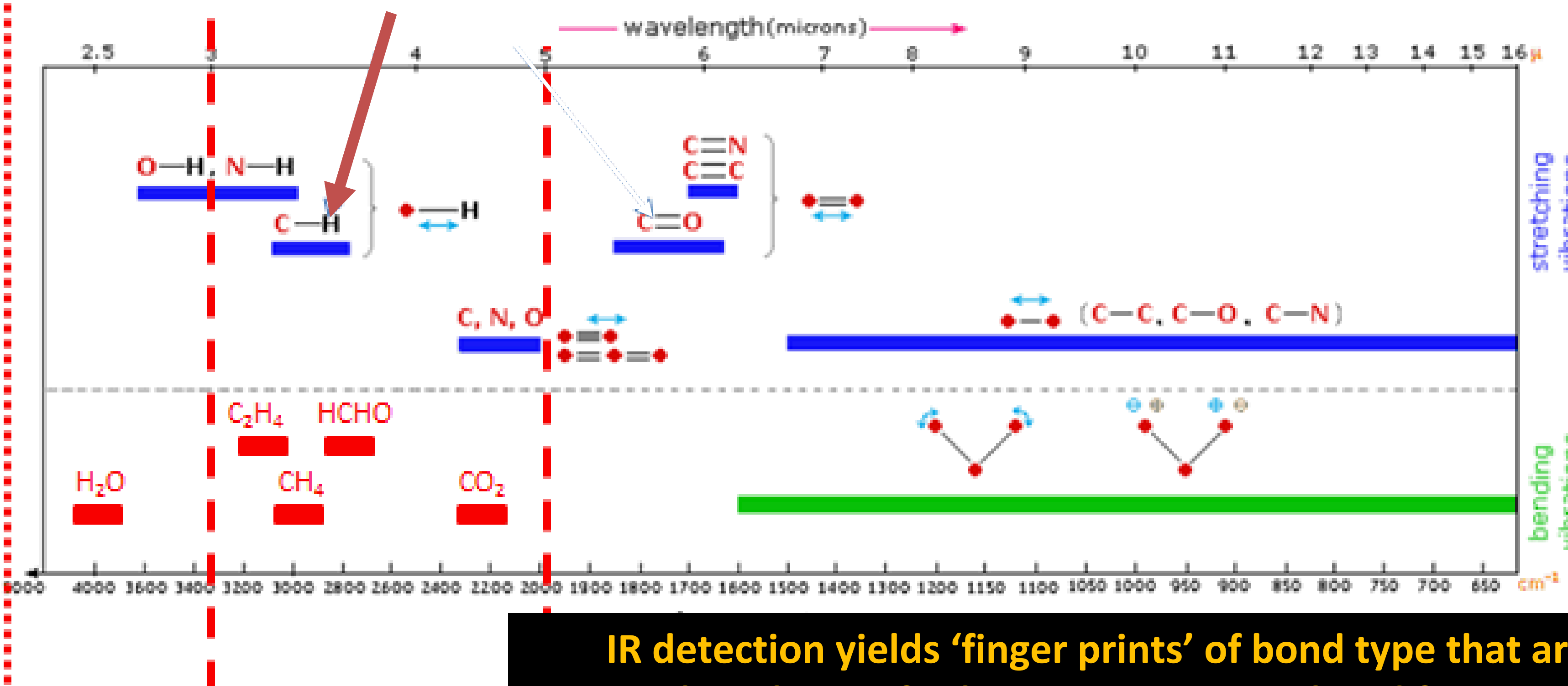
UHC – Unburned Hydrocarbons, LTC – Low Temperature Combustion, PAH- polyaromatic hydrocarbon

Musculus, M. P. B., Miles, P. C., & Pickett, L. M. (2013). *Conceptual models for partially premixed low-temperature diesel combustion*. *Progress in Energy and Combustion Science* (Vol. 39, pp. 246–283). Elsevier Ltd. doi:10.1016/j.pecs.2012.09.001

WHY IR? Prior art - diagnostics

N_2, O_2,…: no dipole moment, no IR radiation.

C-H Stretch at 3.4 Micron

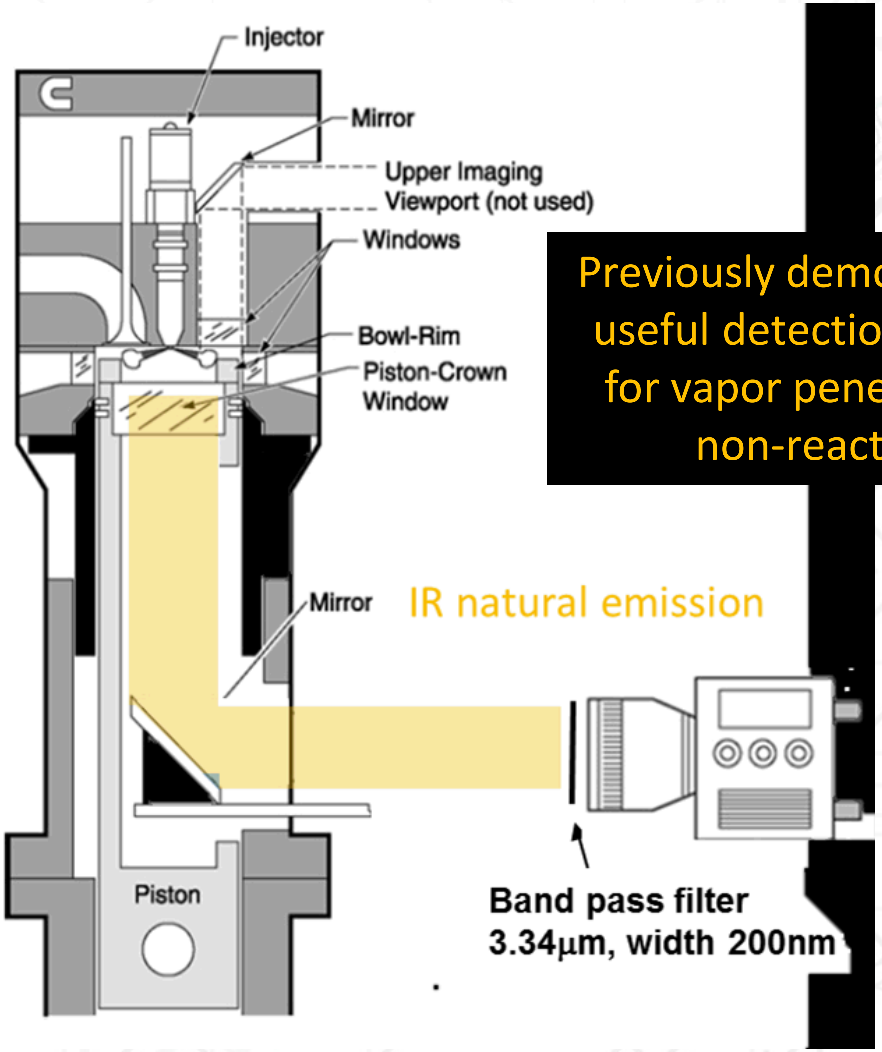


Data from 2008_Jansons_IJER

IR detection yields 'finger prints' of bond type that are wavelength specific, but remain a convoluted function of temperature, concentration, and path length

https://www2.chemistry.msu.edu/faculty/reusch/virttxtjml/Spectrpy/InfraRed/infrared.htm

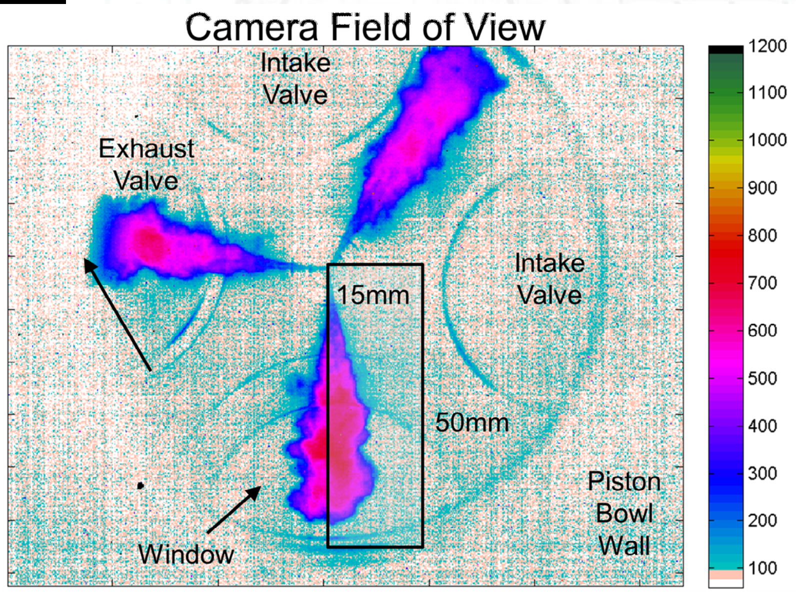
Methods



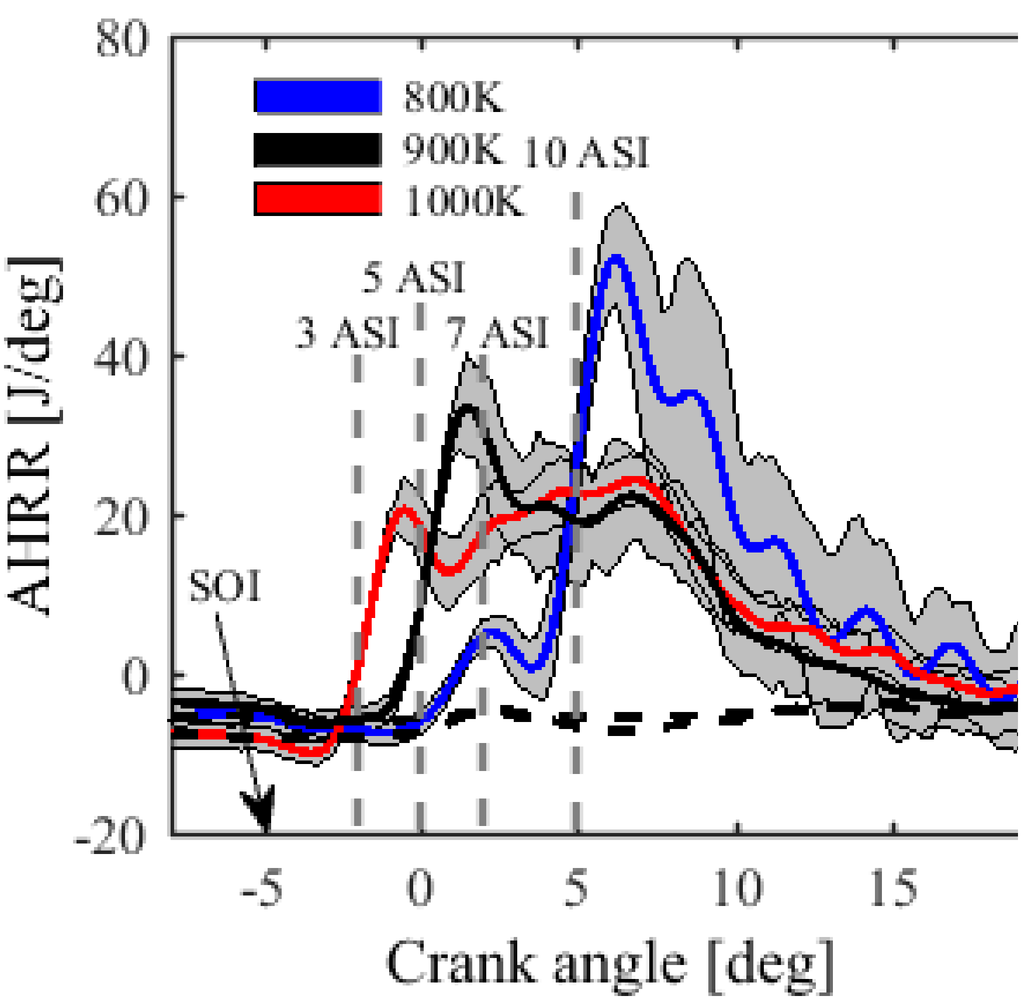
Previously demonstrated useful detection of fuel for vapor penetration, non-reacting

Infrared

- MW-IR (InSb) 3-5μm (TELOPS)
- Lens: 50mm IR f/2.3
- Frame rate: 1 image / cycle
- Exposure: 5μs
- Scale: 4.2 pix per mm

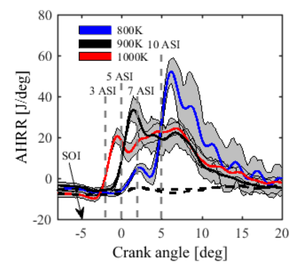


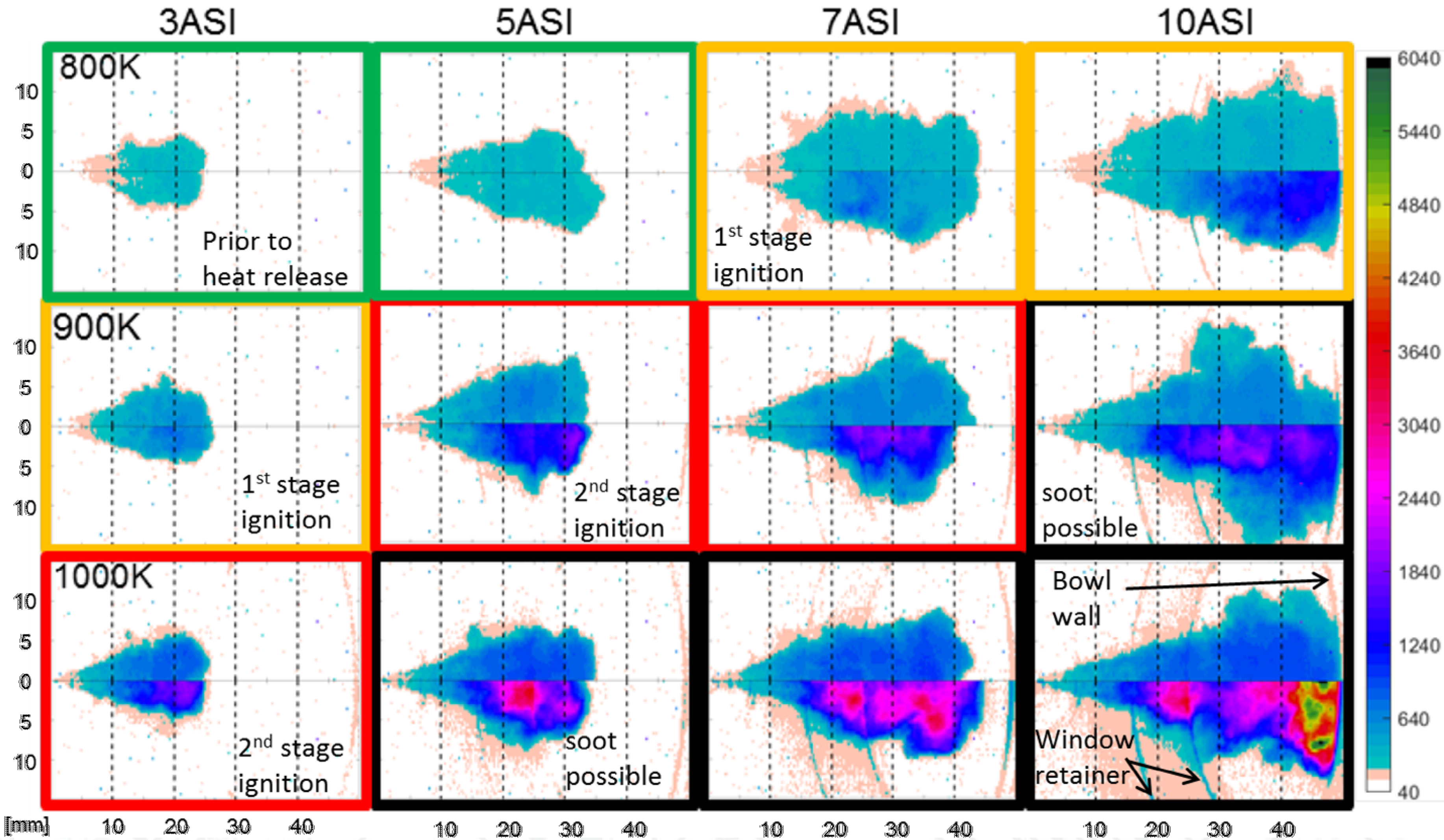
Experimental Conditions



Temperature @ TDC [K]	800	900	1000
Density @ TDC [kg/m^3]	15.2		
Oxygen content [% vol.]	15 , 0		
Injector rail pressure [bar]	1500		
Temperature @ IVC [K]	340	380	454
Pressure @ IVC [bar]	2.01	2.25	2.61
Injected liquid mass [mg/cycle]	3.68	3.68	3.68
Engine Speed [rpm]	1200		
Start of Solenoid Energizing [CAD ATDC]	-6.75		
Start of Injection [CAD ATDC]	-5		
Duration of Solenoid Energizing [CAD], [μs]	5.86, 795		
Injection Duration [CAD],[μs]	11, 1500		

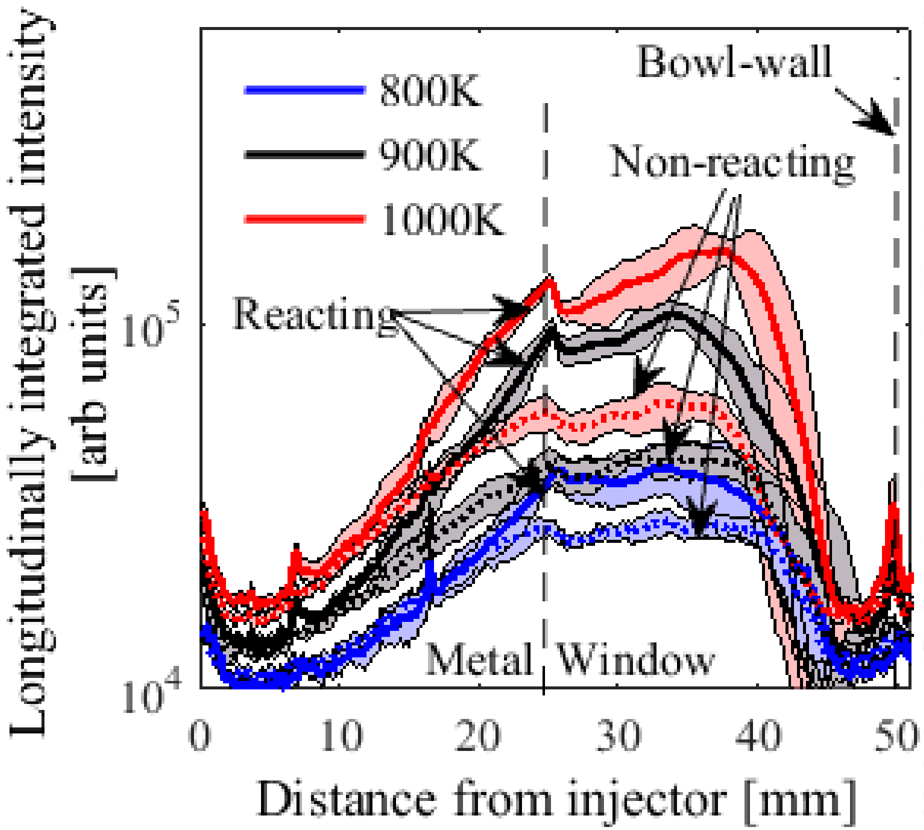
With and Without Reaction

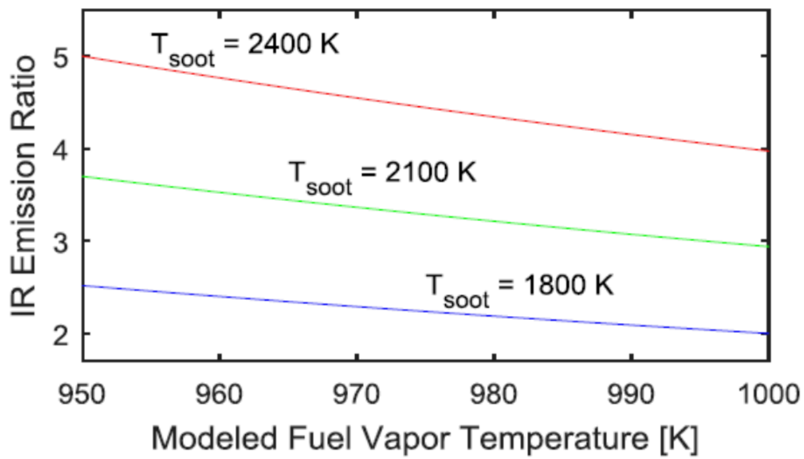




IR appears useful to detect Lift-off.

Limitations and Uncertainty

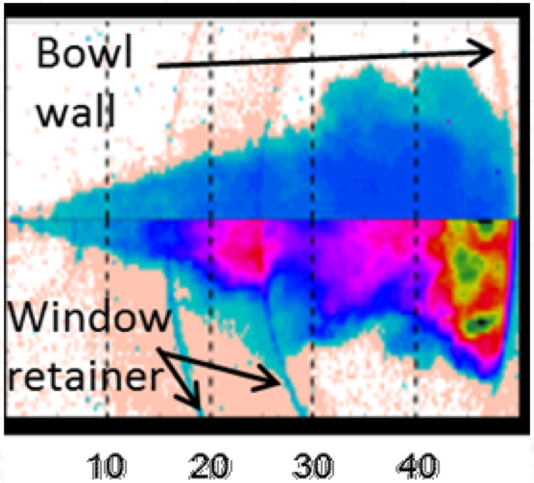




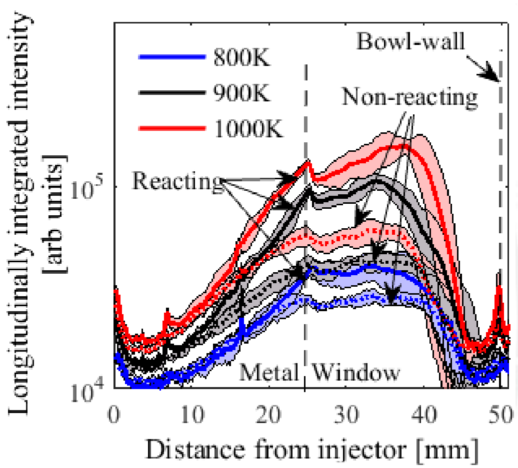
Presence of high temperature soot at relevant concentrations (Spray A) likely overwhelms C-H stretch natural emission

Changes in background reflection strongly influence detected signal.

Summary



IR detection of fuel C-H stretch regions during conventional combustion yields useful engine diagnostic information like fuel vapor penetration and perhaps lift off length.

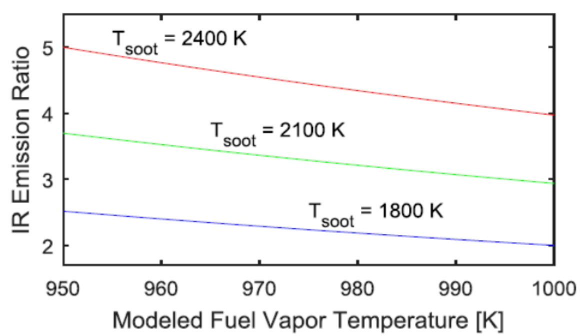


Significant limitations and uncertainties include:

- Changing/non-uniform background reflections
- grey-body radiation from soot

And not discussed here:

- changing soot deposits on window surfaces (not discussed here)
- signal self-absorbance along the line of sight (previous work)



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Current Gaps

Experimental diagnostics that can help identify FORMATION vs OXIDATION of criteria pollutants in-cylinder, for the validation of CFD emissions models.

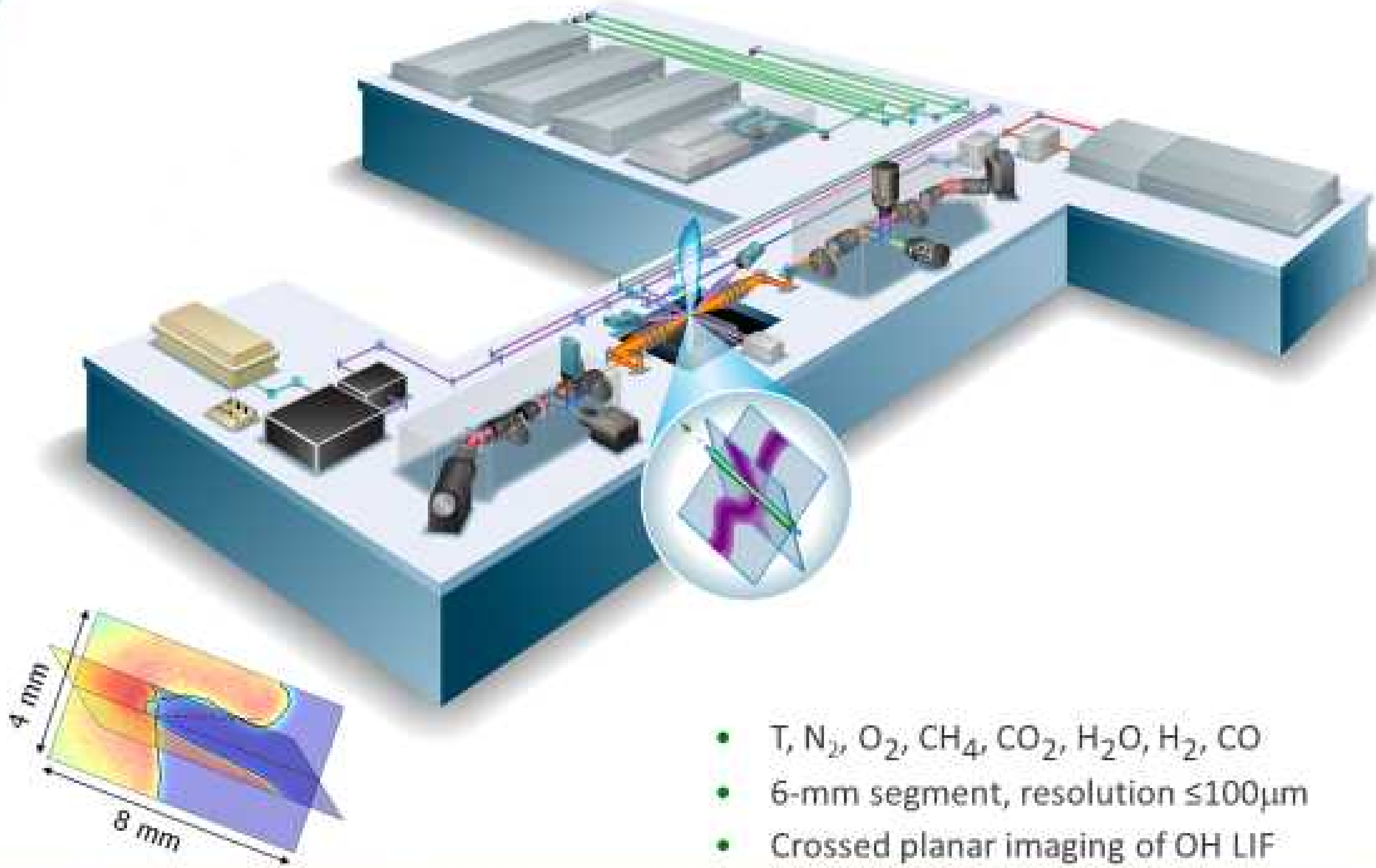
Need all the relevant data to solve Reynolds Transport Theorem!

F(c,T,p,velocity) -> (change with time = transport + production + dissipation)

Coupled Turbulence-Chemistry Problem!?

Need Lagrangians…Time Resolved…

Turbulent Combustion Laboratory



- T, N_2, O_2, CH_4, CO_2, H_2O, H_2, CO
- 6-mm segment, resolution ≤100μm
- Crossed planar imaging of OH LIF

What is (could be) next?

- Identify regions of formation/oxidation by bond type
- Can geometric transformations to recover local data? (Abel inversion?)
- Look for mulit-spectral features that can de-convolve Temp and Concentration dependence (e.g. R. Hanson)
- PIV recording of mean velocity field, strain
- ‘predict’ next time step using experimental measured values of T, c, strain, and transport.
- Compare with next measurement to identify sources of error in modeling.

Scientific barriers to further IR work

- Pressure broadening
- High temp interference e.g. OH, H2O, CO2 (others? un-quantified?) – any suggestions?
- Background non-uniformity(ies)
- Self-absorption (concentration and path length dependent)
- Gradient-induced beam steering between source and detector.

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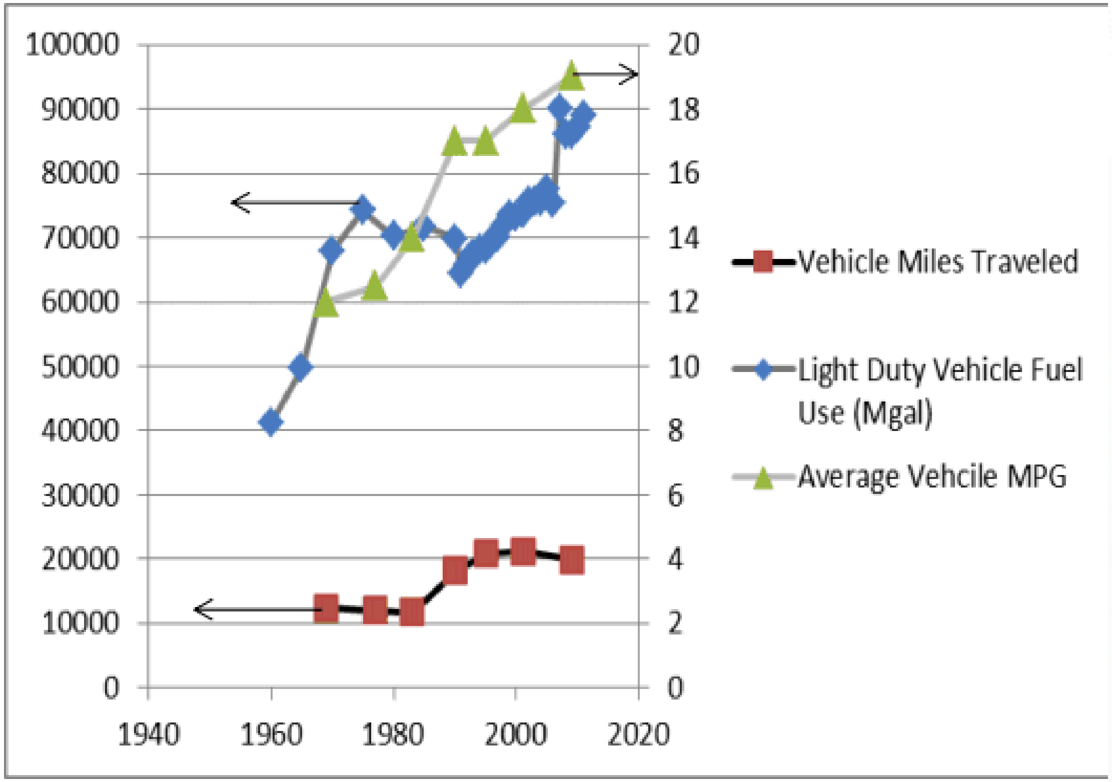
Framing bigger problems...

Technologies that maintain low emissions, reduce noise and maximize system efficiency must be coupled with strategies that combat wasteful use and promote thoughtful consumption.

Jevon's Paradox:
An increase in efficiency with which a resource is used **tends to increase the rate of consumption** of that resource.



Questions?

Spectral modeling of fuel and combustion products demonstrate

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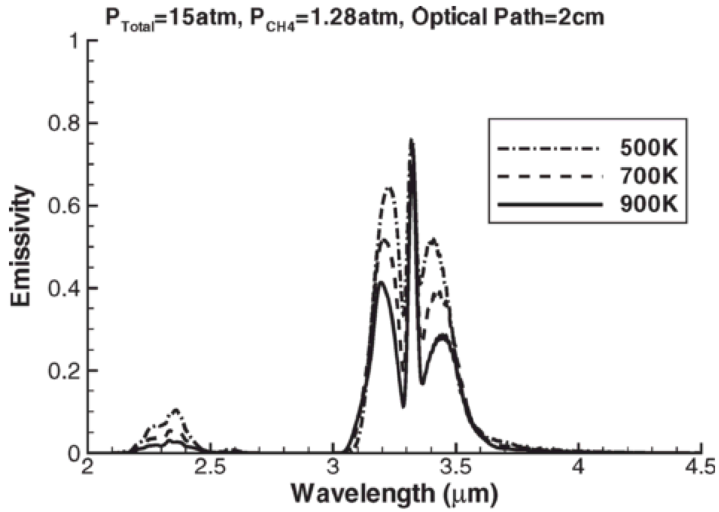
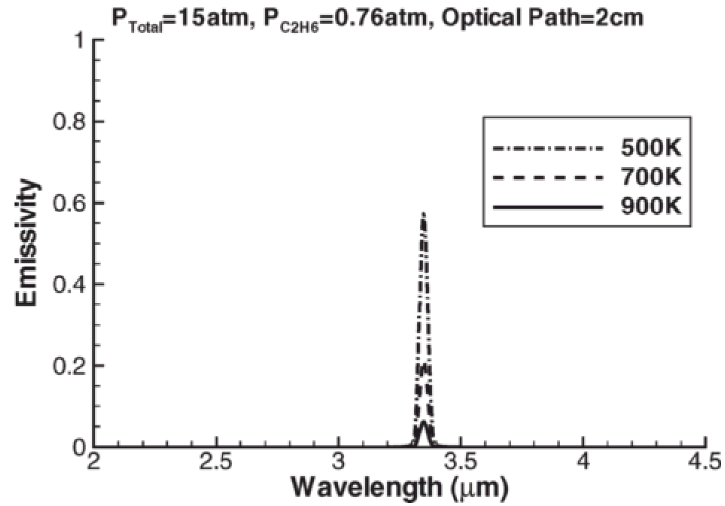
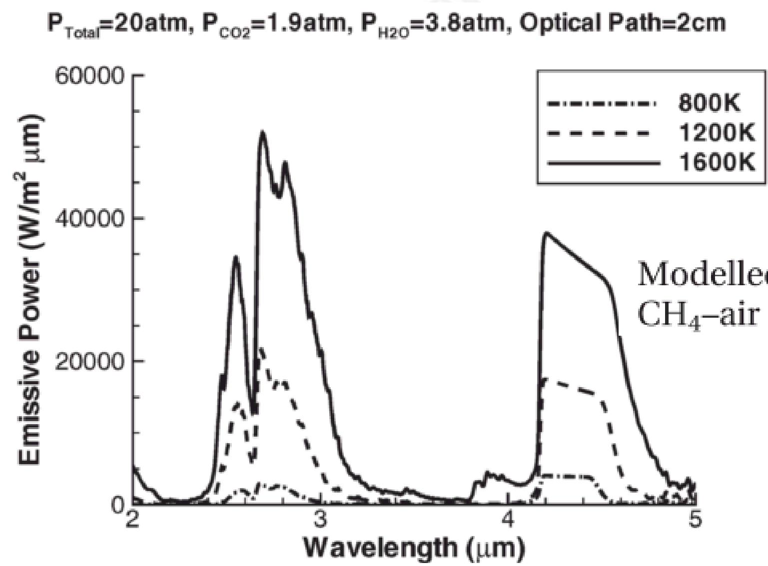


Modelled stoichiometric CH_4–air mixture emission spectrum



Modelled C_2H_6–air mixture emission spectrum



Modelled emissive power of stoichiometric CH_4–air combustion product mixture

M. Jansons, S. Lin and K Rhee Infrared spectral analysis of engine preflame emission IJER 2008

WHY IR? Prior art - diagnostics

Species detection – 1D measures

SAE 2007-01-0644: Grosch (Laser-Lab Gottingen). Fuel absorption @3.39µm (using a He-Ne laser) . SI engine. Fuel concentration near spark plug. Sapphire fiber, no absorption @ 3.39 µm.

SAE 2007-01-0639: Kakuho (Nissan), Hanson (Stanford). 2 colors Water absorption in near IR (around 1.4µm) + modulation. SI engine. Residual gas concentration and temperature near spark plug.

SAE 2007-01-1849: Kawahara (Obayama Univ.) CO2 absorption at 4.26µm . SI engine. Residual gas concentration.

SAE 2006-01-3337: De Francqueville (IFPEN). CO2 absorption at 4.26µm. SI engine. Residual gas concentration.

Species detection – 2D measures

SAE 1999-01-3494: Jansons (Rutgers). IR camera 2000Hz DI Diesel engine. Simultaneous IR emissions @ 2.2µm, 2.47µm (water), 3.42µm (preflame) and 3.8µm (soot). Qualitative images.

SAE 2000-01-1800: Jansons (Rutgers). IR camera 2000Hz SI and DI Diesel engines. Simultaneous IR emissions @ 2.2µm, 2.47µm (water), 3.42µm (preflame) and 3.8µm (soot). Qualitative images.

IJER 2008 9:215: Jansons (Wayne State), Lin & Rhee (Rutgers). IR camera 1880Hz SI and DI Diesel engines. Simultaneous IR emissions @ 2.1µm, 2.47µm (water), 3.43µm (preflame) and 3.8µm (soot). HITRANS modelling. HCHO signal week for SI engines.

SAE 2011-01-1395: Squibb (Michigan State). FLIR Phoenix MID, 60Hz. 3-5µm. 20µs integration time. Fuel sprays and combustion visualization. In-cylinder temperature.