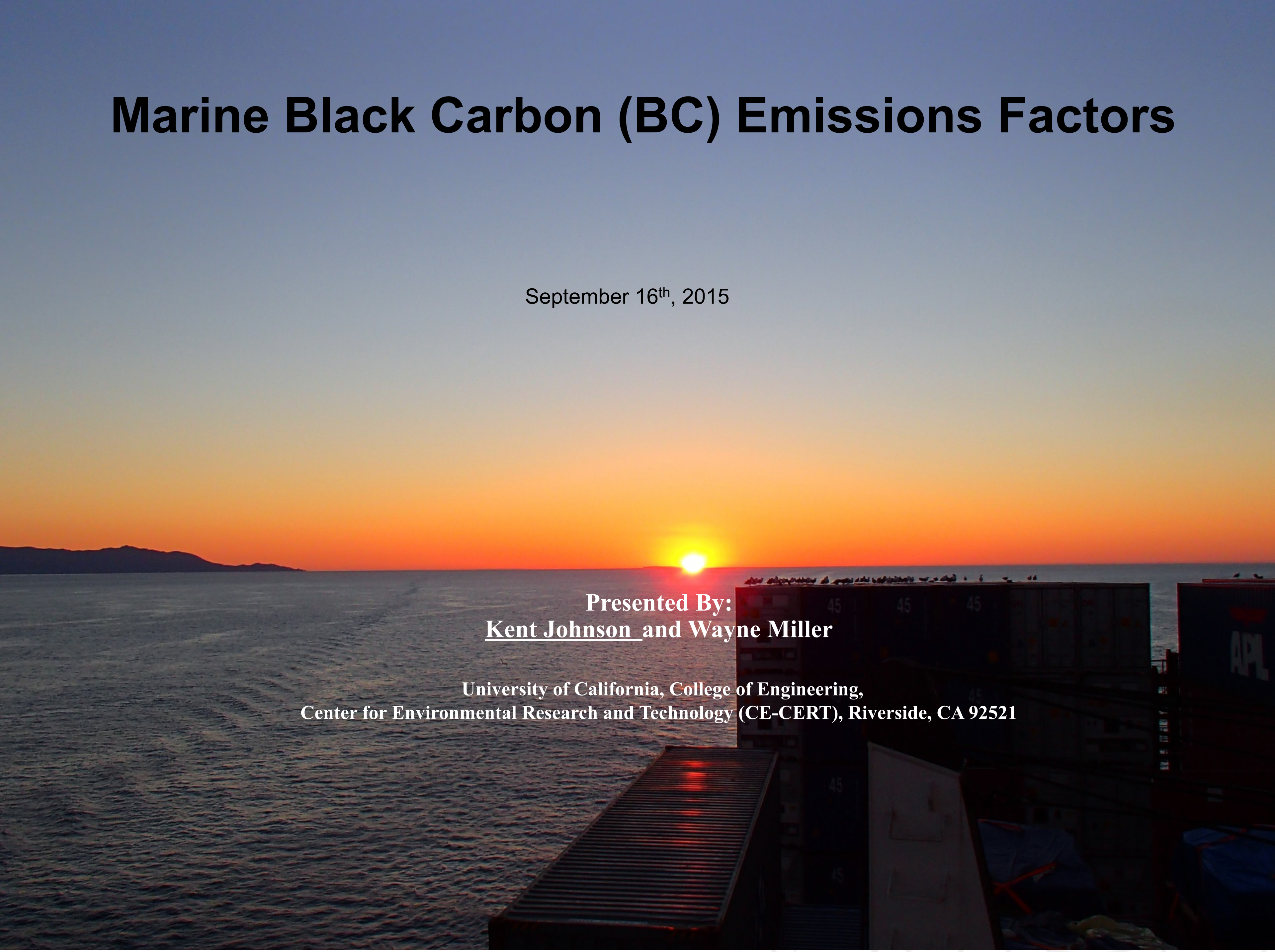

Marine Black Carbon (BC) Emissions Factors

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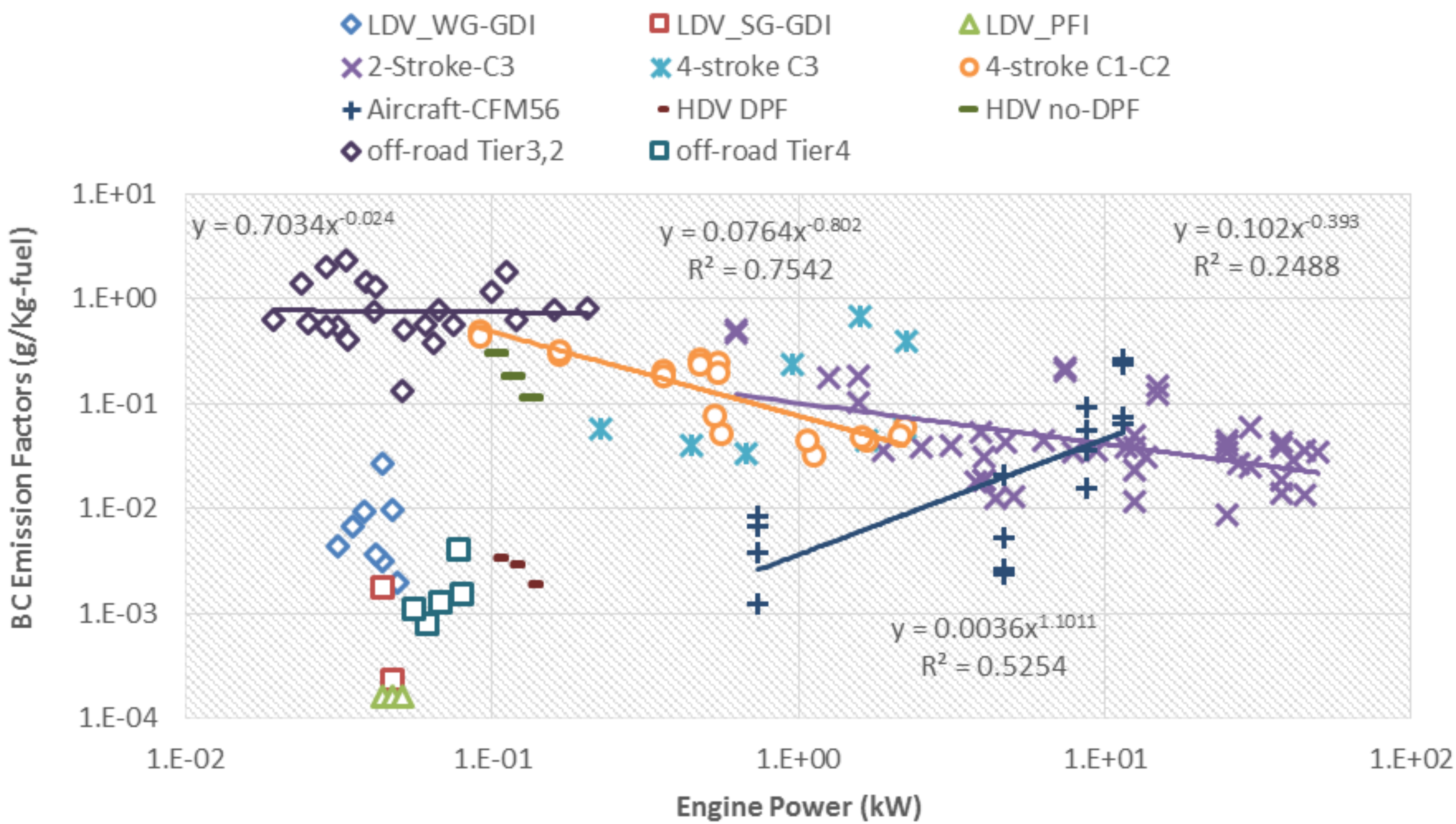
Black Carbon Questions

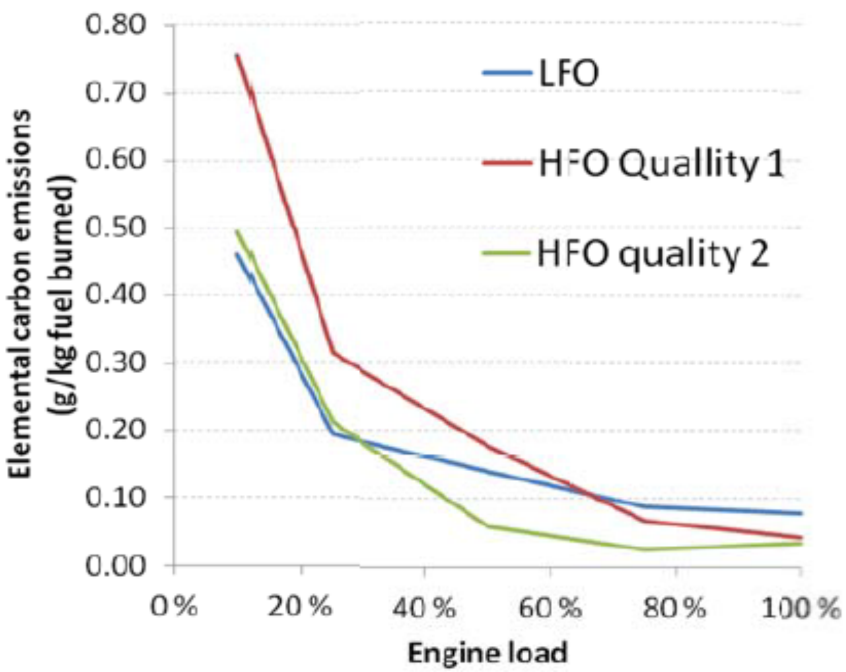
- How do BC emission factor (EF) vary?
  - Fuels
  - Loads
  - Sources
  - Dilution

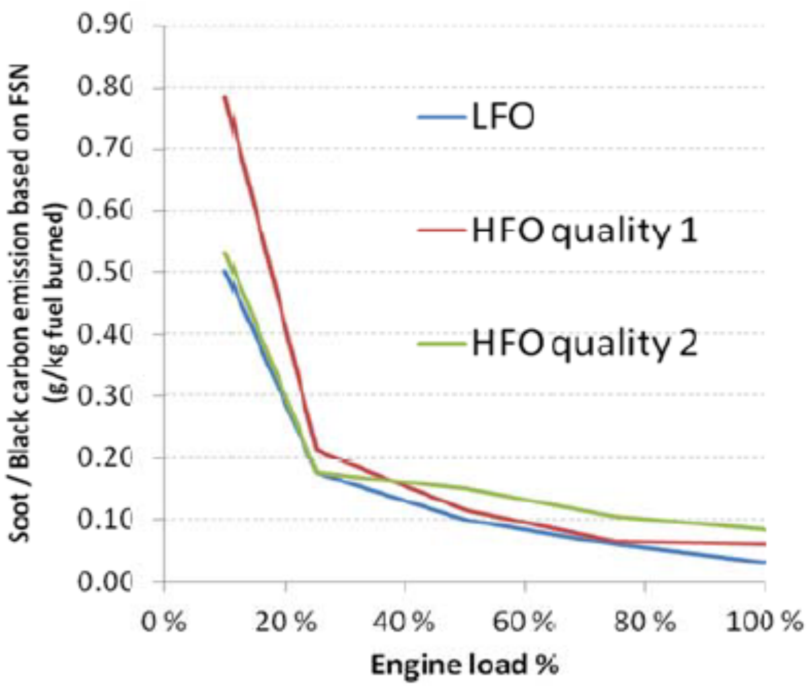
- Are all BC measurements comparable?

EFs Vary by Vocation



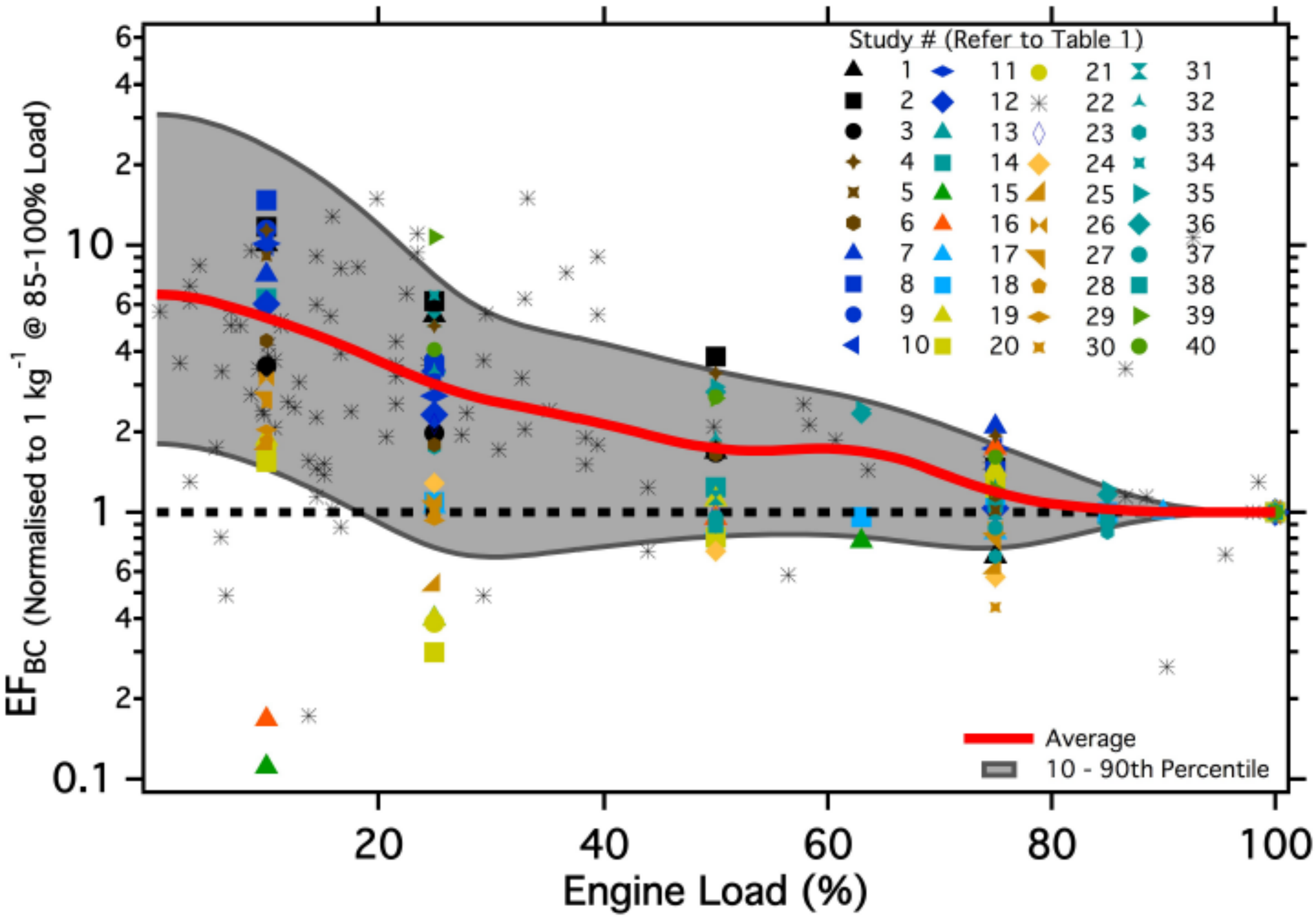
EFs Vary with Load Factor





(source Watsilla)

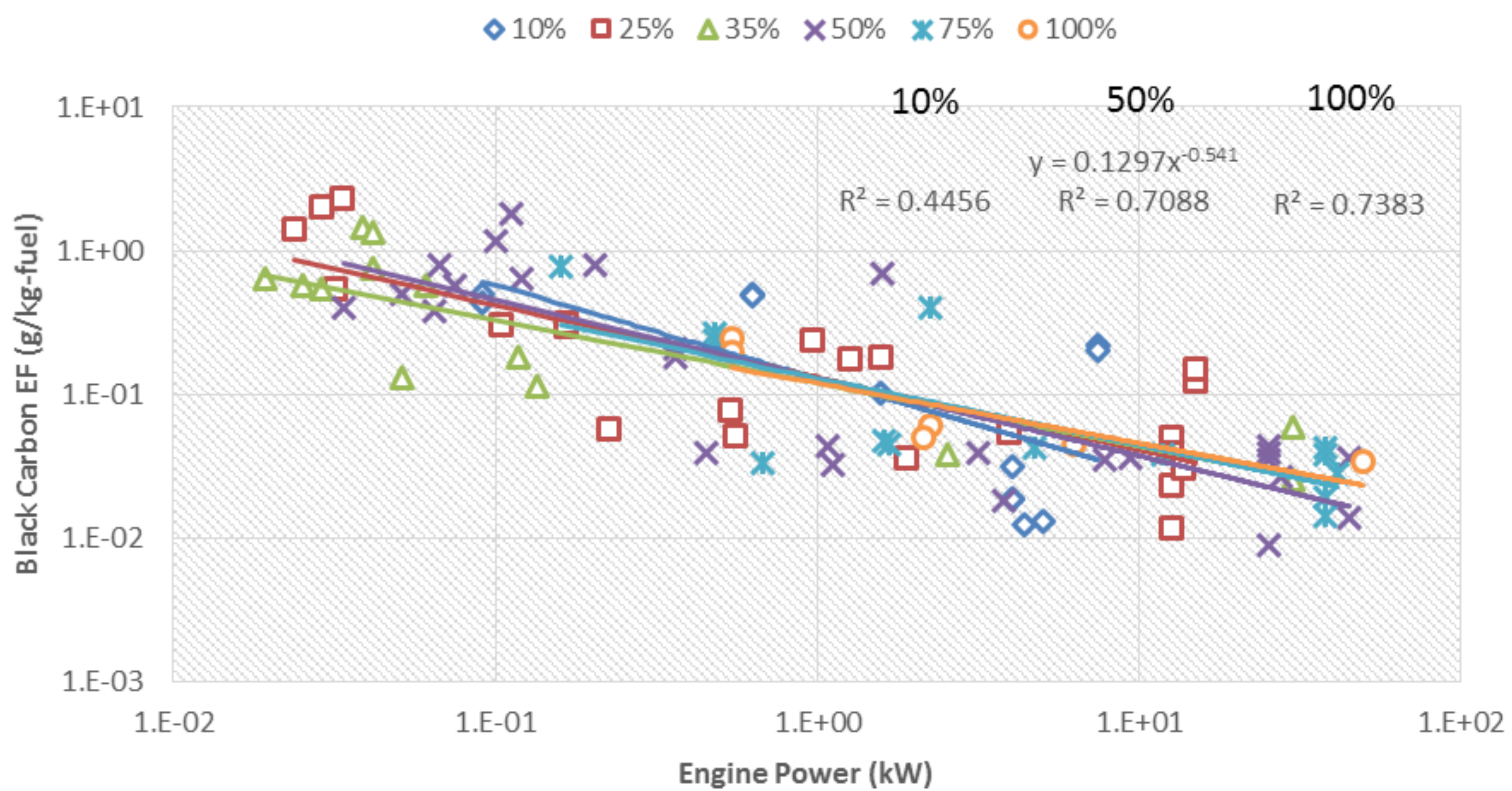
Plume Studies Show Similar Trend



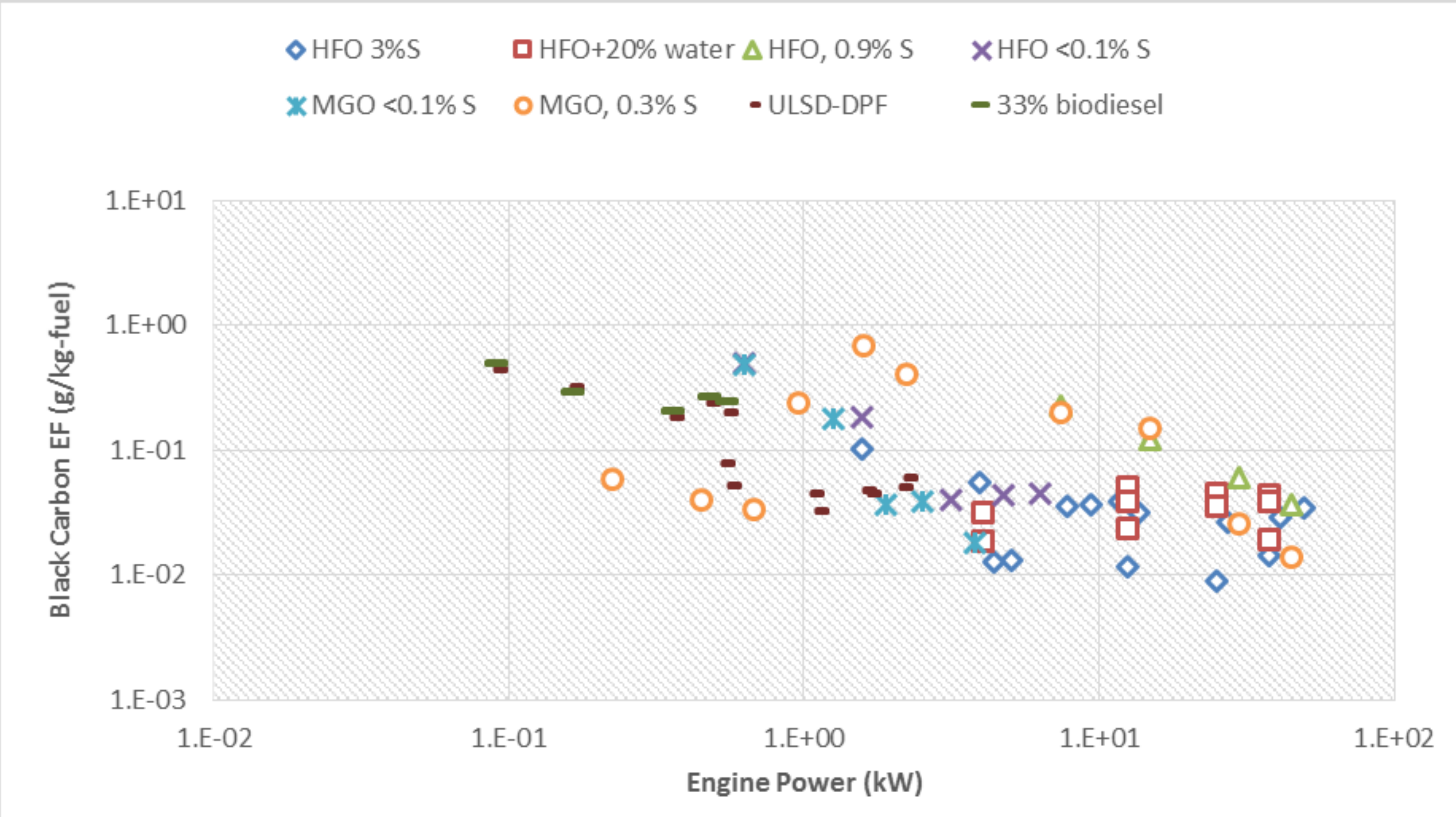
BC (g kg^{-1}) Average ± S.D.
0.41 ± 0.27
0.97 ± 0.66
0.36 ± 0.23
0.38 ± 0.27
0.80 ± 0.23
0.40 ± 0.23
0.38 ± 0.16
0.97 ± 0.66
0.36 ± 0.23

(source Lack et al 2012)

EFs Increase with Smaller Size



EFs Also Vary with Fuel

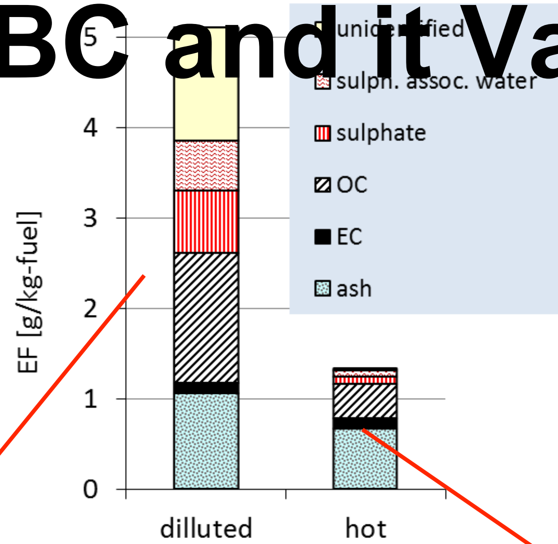


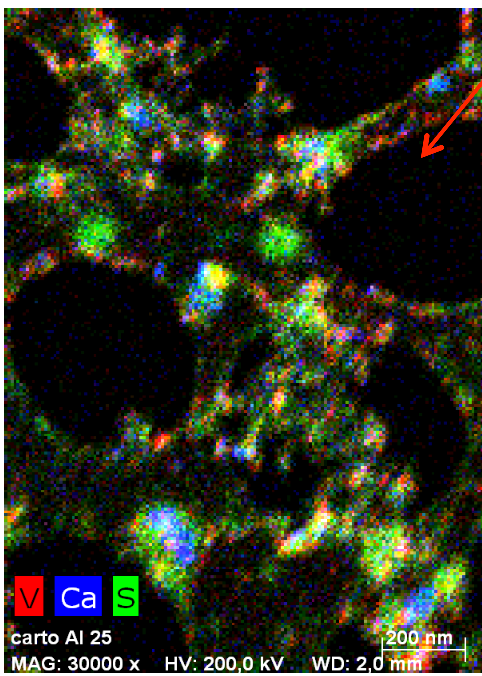
Published BC EF Differences

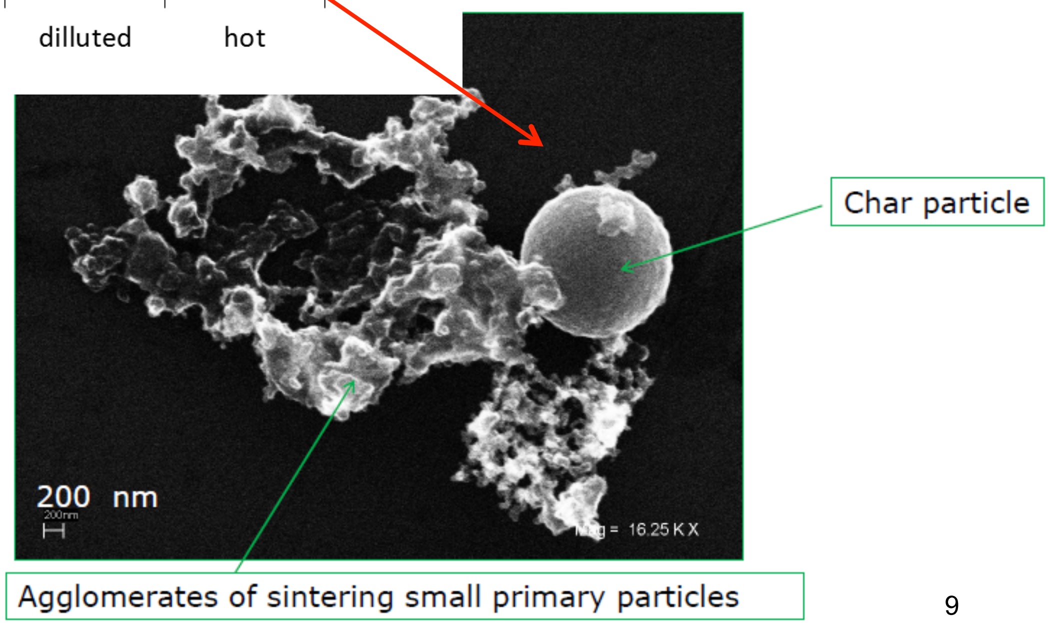
BC emission fuel burned	g/kg fuel	Method of determination
Lack et al	0.36 -1	Optical/photoacoustic
Agrawal et al	0.1	Thermal
Corbett et al	0.37	
Petzold et al	0.179 ± 0.018	Optical
Petzold et al	0.06 (85% load) 0.36 (10% load)	Optical

- Variability between reported EF varies by factor of 10
- Measurements varied from optical, thermal, and photo acoustic
- Measurements varied from stack to plume sampling (10:1 vs > 1000:1 dilution)

PM is Composed of Various Coatings on BC and it Varies with Dilution







Source: Moldanova et al ICCT 2014 workshop

Source of BC EF Biases: Measurements Issues?

- Light absorbing carbon measurement methods (filter absorption methods) don't measure BC and need good assumptions about BC mass absorption which varies.
- Laser incandescence (SP2 approach)
  - Loosely packed agglomerates behave as individual particles causing the measurement response differences (Gysel M. et al 2012)

M. Gysel1, **M. Laborde**1, **A. A. Mensah**2, **J. C. Corbin**2, **A. Keller**3, **J. Kim**4, **A. Petzold**5, **and B. Sierau**2 **Technical Note: The single particle soot photometer fails to reliably detect PALAS soot nanoparticles,** Atmos. Meas. Tech., 5, 3099–3107, 2012

Source of BC EF Biases: Measurements Issues?

- Thermal optical methods (NIOSH/IMPROVE) may be influenced by the PM coatings
- Filter Smoke Number/Meter is requires calibration and could vary with total PM concentration and PM coatings.
- Photoacoustic and LLI (laser incandescence) methods are more direct, but require calibration which requires assumptions

Recommendations

- Quantify/identify possible interferences of measurement methods
  - As fuel, load, and engine type vary
  - BC measurement systems: LAC types, Thermal optical, and Photo acoustic
- Suggest and recommend BC pre-sample conditioning
  - Thermo-denuder, dilution, temperatures, residence time.

Backup

Combustion Soot Formation

(Liquid Fuel)

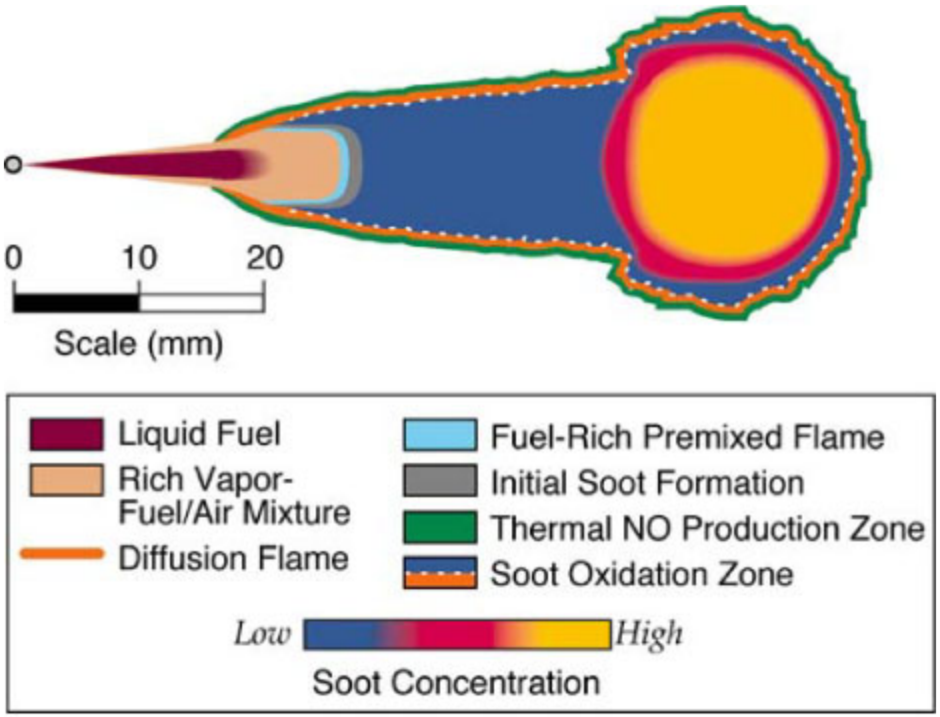


Figure 1. Quasi-steady Diesel combustion plume as presented by DEC (1997). Courtesy Dr. John E. Dec (Sandia National Laboratories).

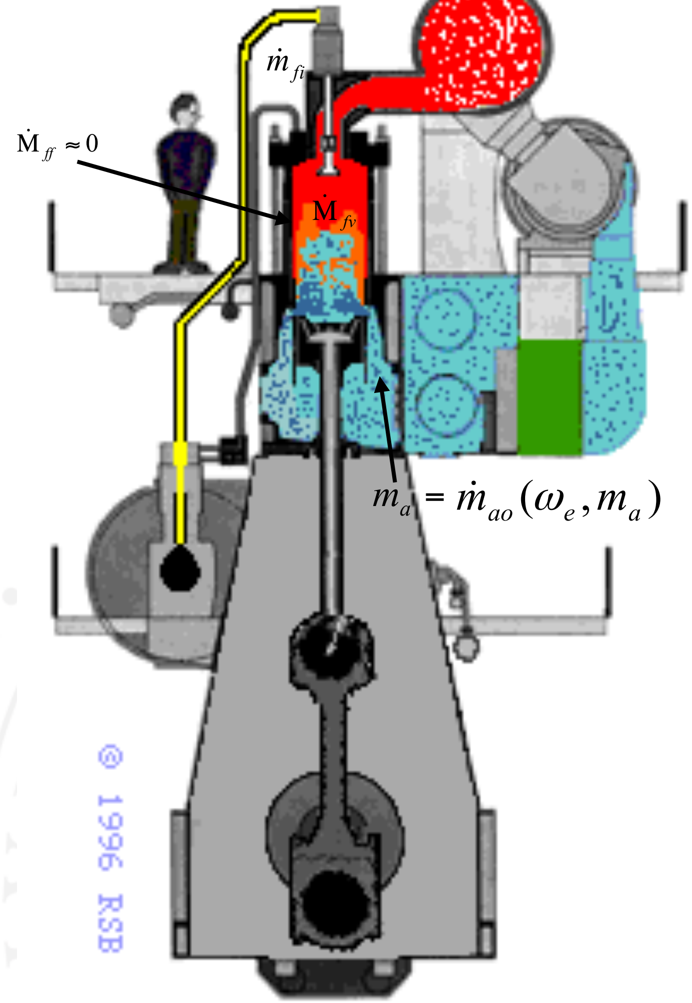
- Industry conditions
  - Engine speed
    - Diesel (3600, 2100, 800, 75 rpm)
    - Gasoline (up to 10,000 rpm)
  - Fuel quality (distillates, residual, sulfur level)
- Operational conditions
  - Fuel control issues (engine speed/load vs load only change)
- Mitigation and Controls
  - Catalyst, diesel particulate filters (distillates)
  - Scrubbers (residual fuels)
- Solid fuel combustion
- Gaseous fuel combustion

Marine 2-Stroke Combustion

- Cross head type
- Inlet ports uncovered by piston motion, not valves
- Forced scavenging
- Low speed (60-90 rpm) → fuel well mixed with air even with low quality fuels

$$m_a = \dot{m}_{ao}(\omega_e, m_a)$$

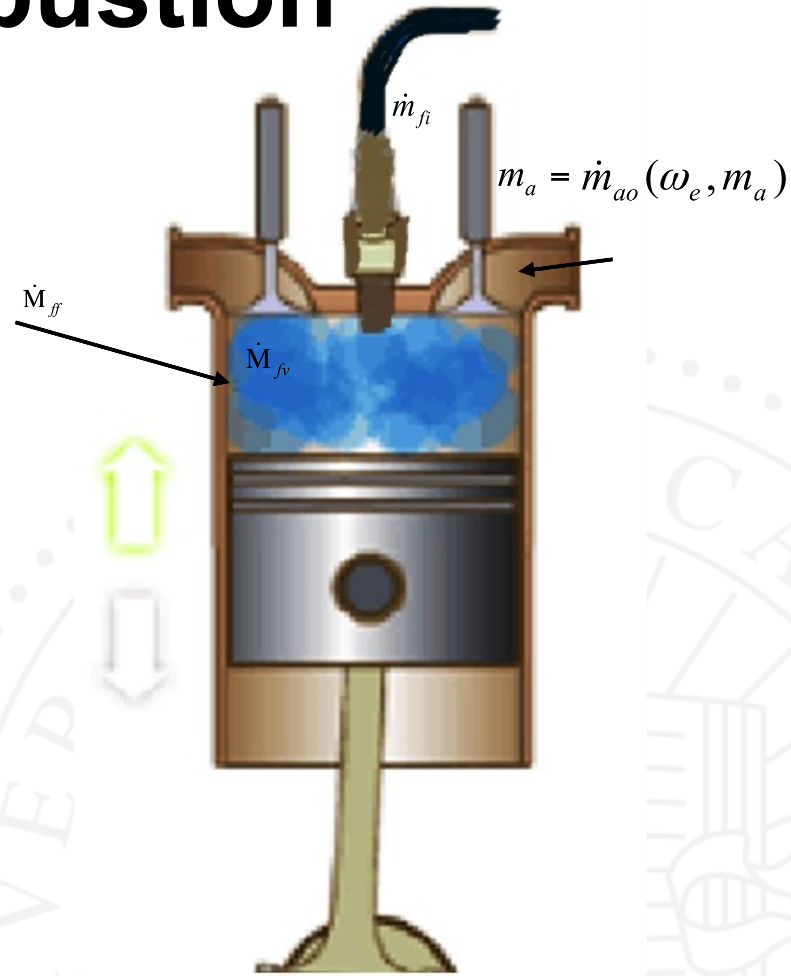
$$m_{fi} = \dot{m}_{fv} + \dot{m}_{ff}$$



Large Sulzer 2-stroke cartoon
Ref: http://www.reddit.com

4-Stroke Diesel Combustion

- High power medium RPM range engines (1000 – 2000 rpm)
- No intake air throttling
- Air/fuel injection less dynamic than LDV, but more dynamic than large 2-stroke



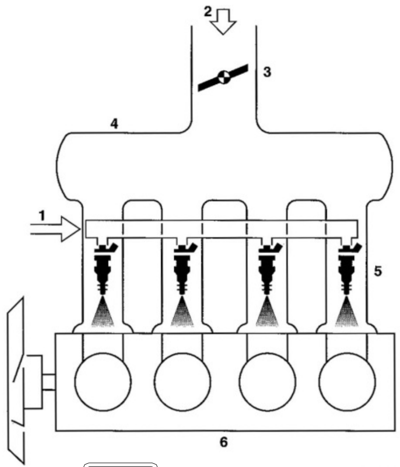
$$m_a = \dot{m}_{ao}(\omega_e, m_a)$$

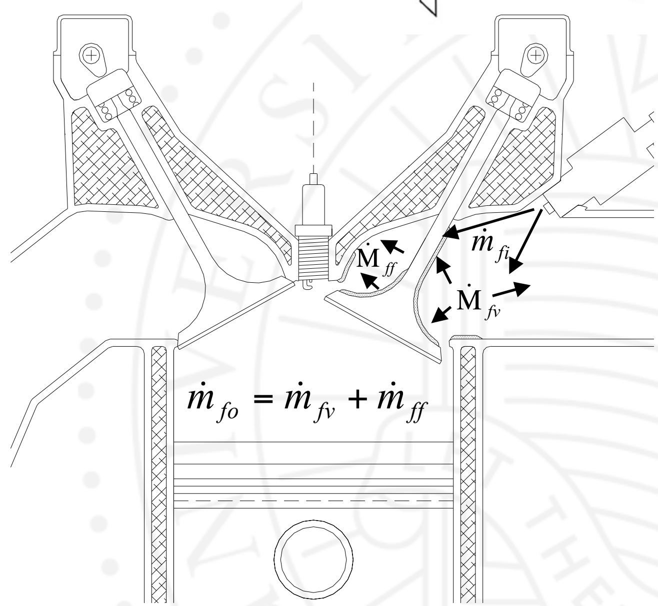
$$m_f = \dot{m}_{fv} + \dot{m}_{ff}$$

4-stroke CI. Modified from
Ref: World press

Spark Ignited Engine Combustion

- Fuel injected outside of the cylinder onto the back of the valve and intake manifold
- Complex film and fuel delivery equations





$$\dot{m}_{fv} = (1-\chi)m_{fi}$$

$$\dot{m}_{ff} = \lambda \mathrm{M}_{f}$$

$$\dot{m}_{fo} = \dot{m}_{fv} + \dot{m}_{ff}$$

Ref: Bosch and K Johnson 2004