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# An Introduction to Ducted Fuel Injection & Its Potential to Facilitate Practical, Clean, & Sustainable Vehicles & Machines for the Future

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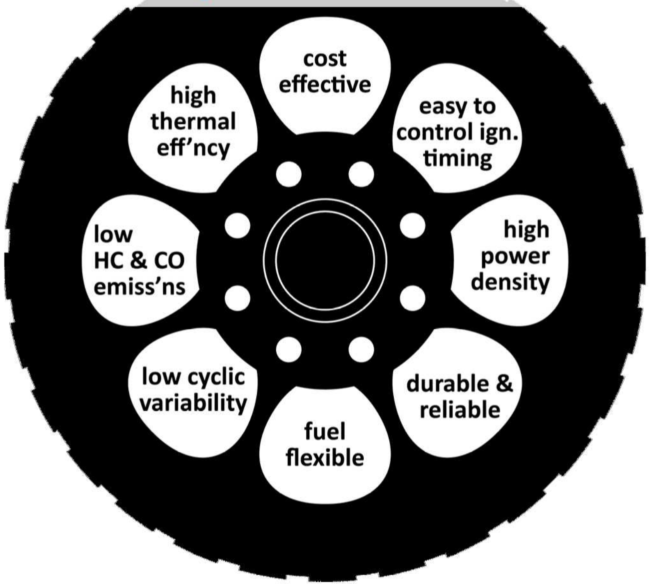
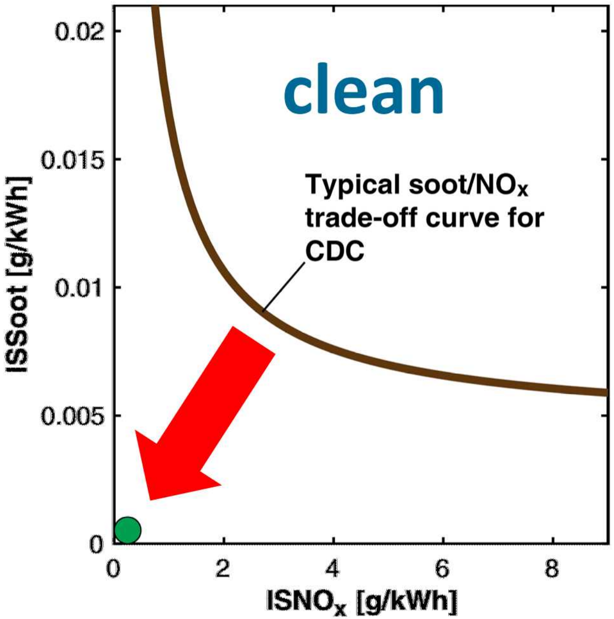
# Objective: Preserve all the desirable attributes of conventional diesel combustion (CDC)…

practical




clean



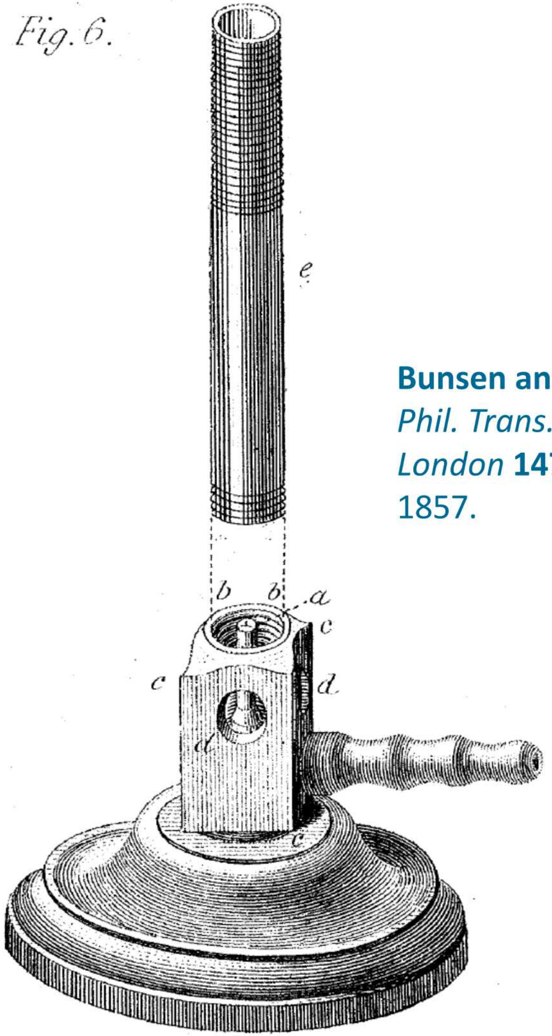

sustain-able

…with 10X – 100X lower soot & nitrogen oxides ($NO_x$) emissions

…while harnessing synergies with sustainable, home-grown fuels.

# Ducted fuel injection (DFI) shows promise for achieving this vision.

- **Simple, mechanical approach**
  - Motivated by Bunsen burner concept

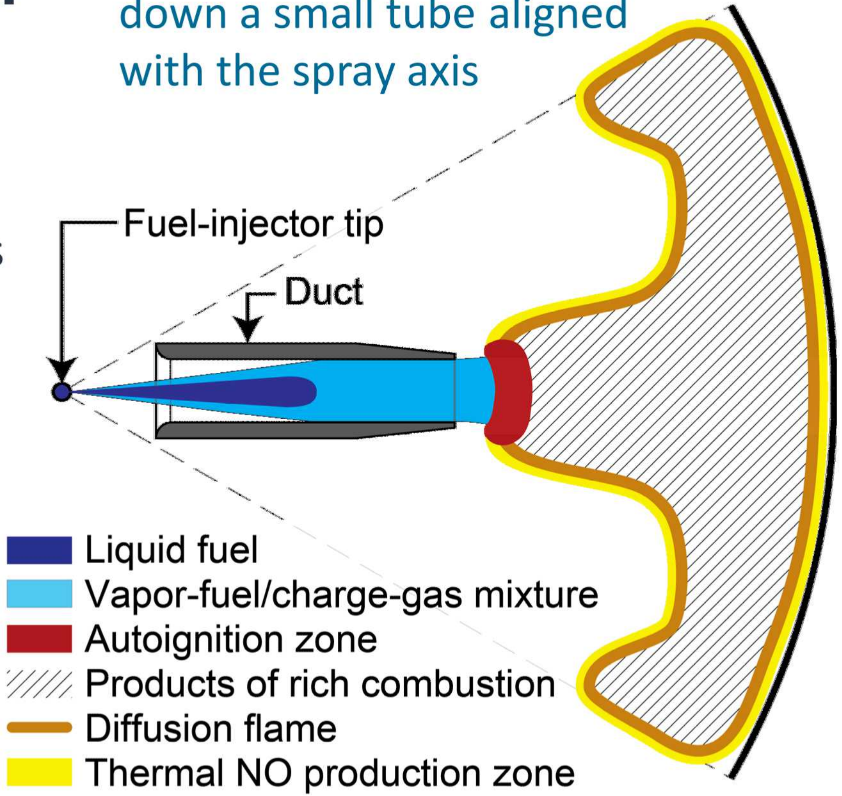



**Bunsen and Roscoe,** *Phil. Trans. Royal Soc. London* **147**:355-380, 1857.

# Ducted fuel injection (DFI) shows promise for achieving this vision

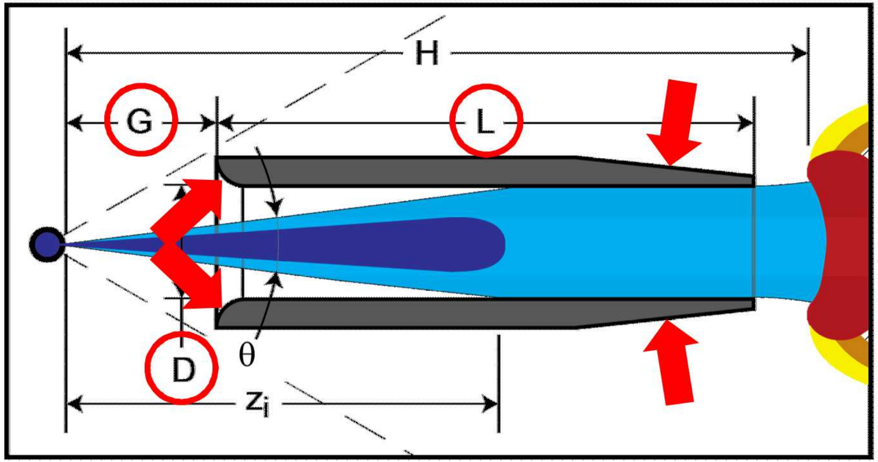
- **Simple, mechanical approach**
  - Motivated by Bunsen burner concept
  - Modifies mixture, thermal, & velocity fields
  - A refinement of CDC → behaves similarly
- **Recent engine experiments have shown that DFI is:**
  1. Effective at curtailing/eliminating **soot**
  2. Tolerant to dilution for simultaneous, cost-effective control of **$NO_x$** emissions
  3. Compatible with diesel fuel & synergistic with oxygenated **renewable fuels**
  4. Viable over a **range of oper. conditions**

**Basic idea:** inject the fuel spray down a small tube aligned with the spray axis

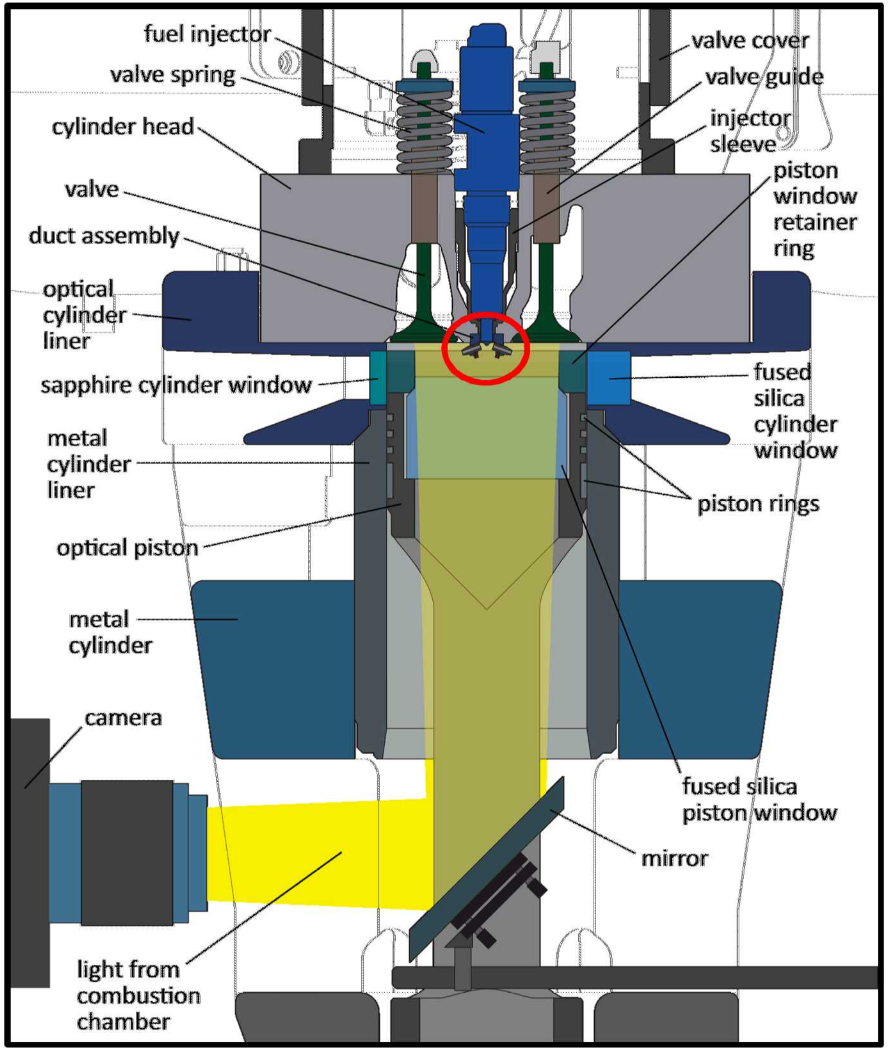



**Mueller et al.**, doi:10.1016/j.apenergy.2017.07.001

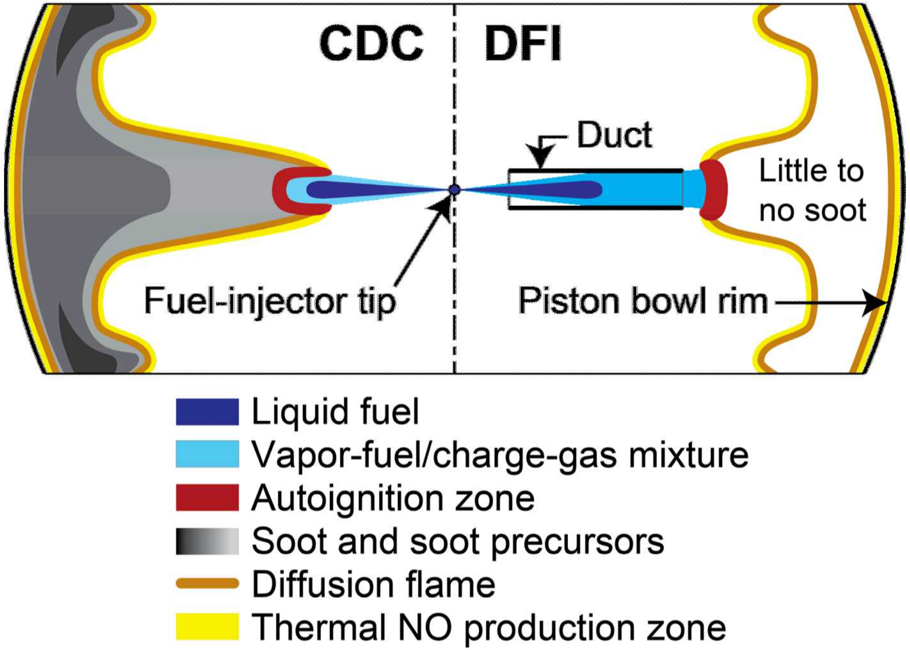
# DFI experiments have been conducted using one-, two-, & four-duct configurations.

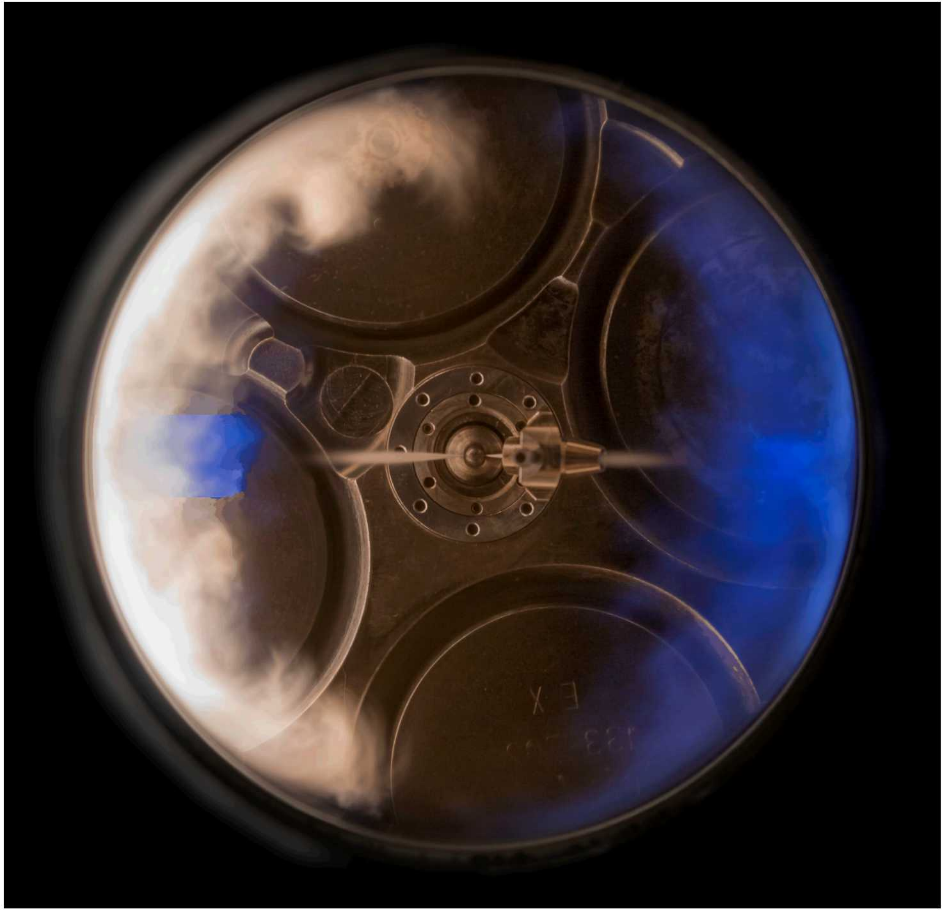



- **Key duct parameters** D2L12G3δ
  - Inner diameter (D [mm])
  - Length (L [mm])
  - Standoff distance (G [mm])
  - Inlet/outlet shape (Greek letter)

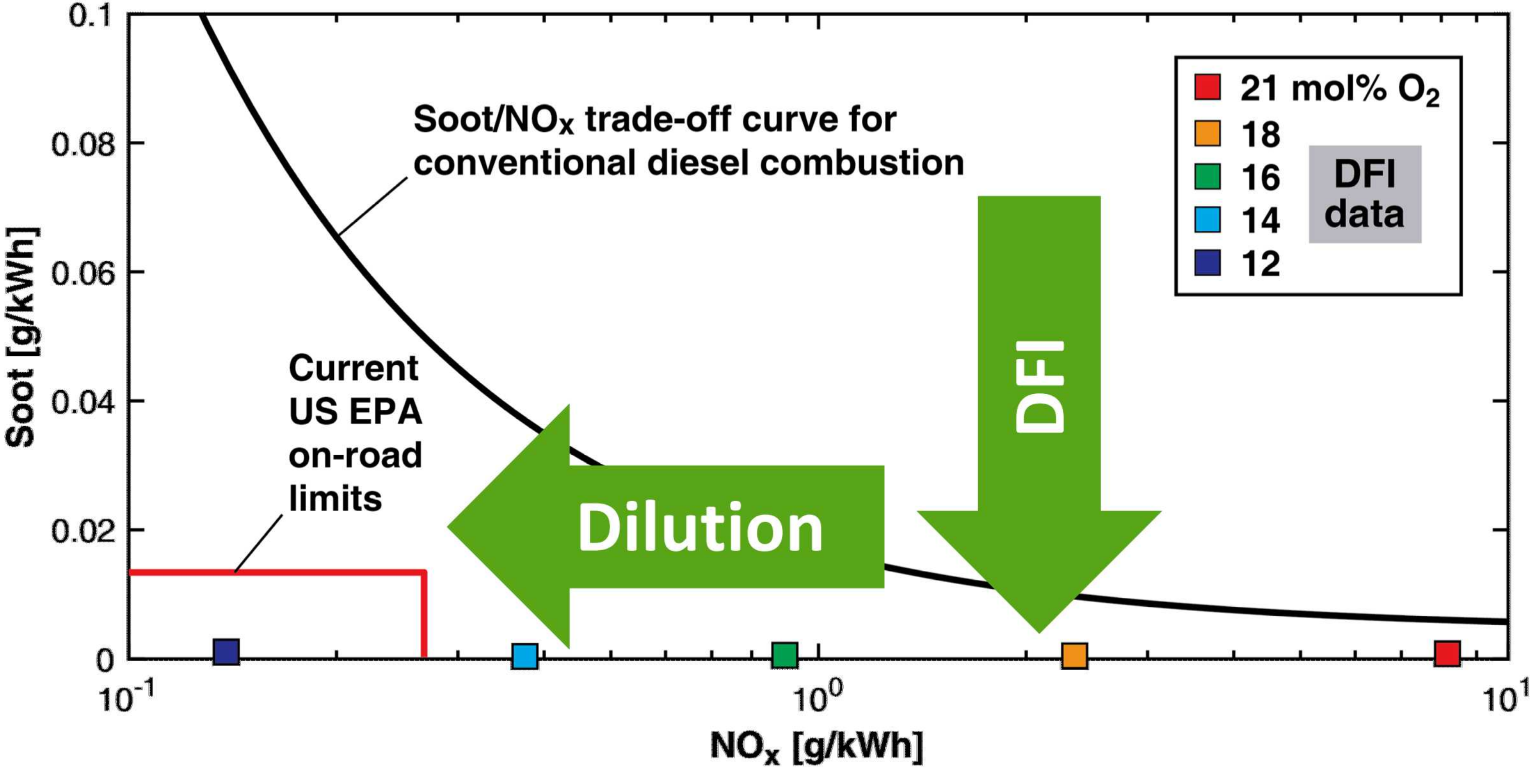


# 1. DFI dramatically curtails soot production in engine experiments.



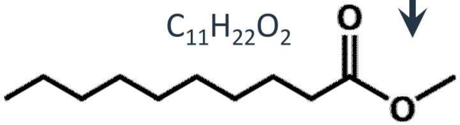
# 2. DFI $NO_x$ can be controlled via dilution without excessive soot, breaking the soot/$NO_x$ trade-off.



# Recent experiments have explored the effects of fuel oxygenation on DFI.

- **Three (3) fuels:**
  - **CFB** = No. 2 S15 emissions certification diesel fuel
  - **MD25** = 25 vol% methyl decanoate (ester) in CFB

$C_{11}H_{22}O_2$

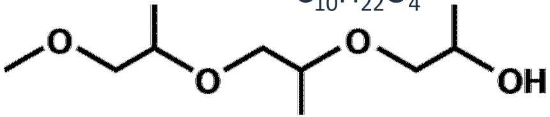


$$\phi_{\Omega,MD25} = \frac{2n_C + \frac{1}{2}n_H}{n_O} = 73.4$$

(see SAE 2005-01-3705 for details)

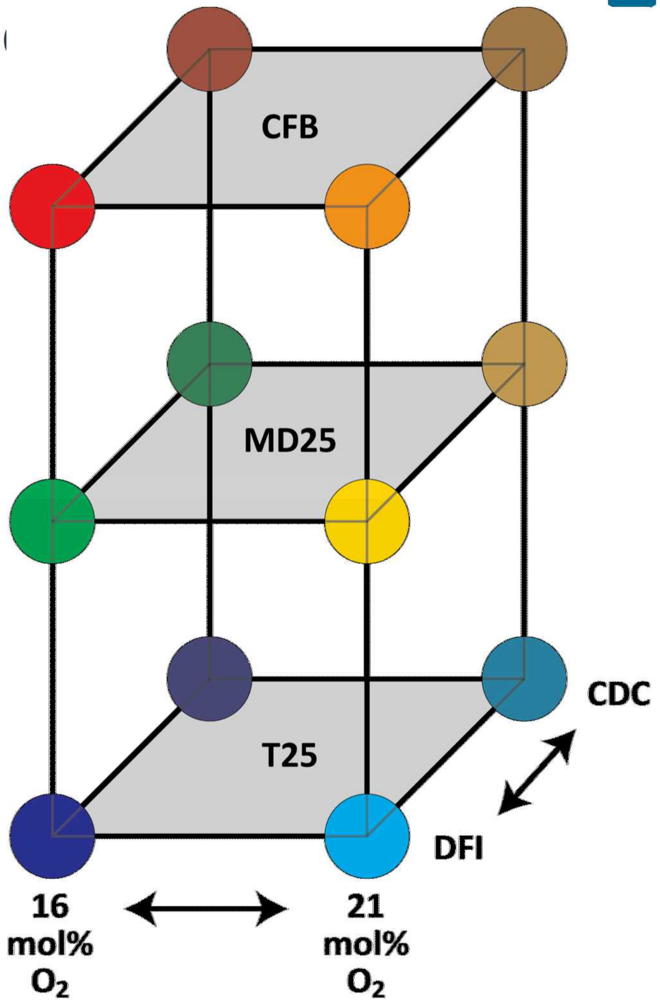
  - **T25** = 25 vol% tri-propylene glycol mono-methyl ether in CFB

$C_{10}H_{22}O_4$

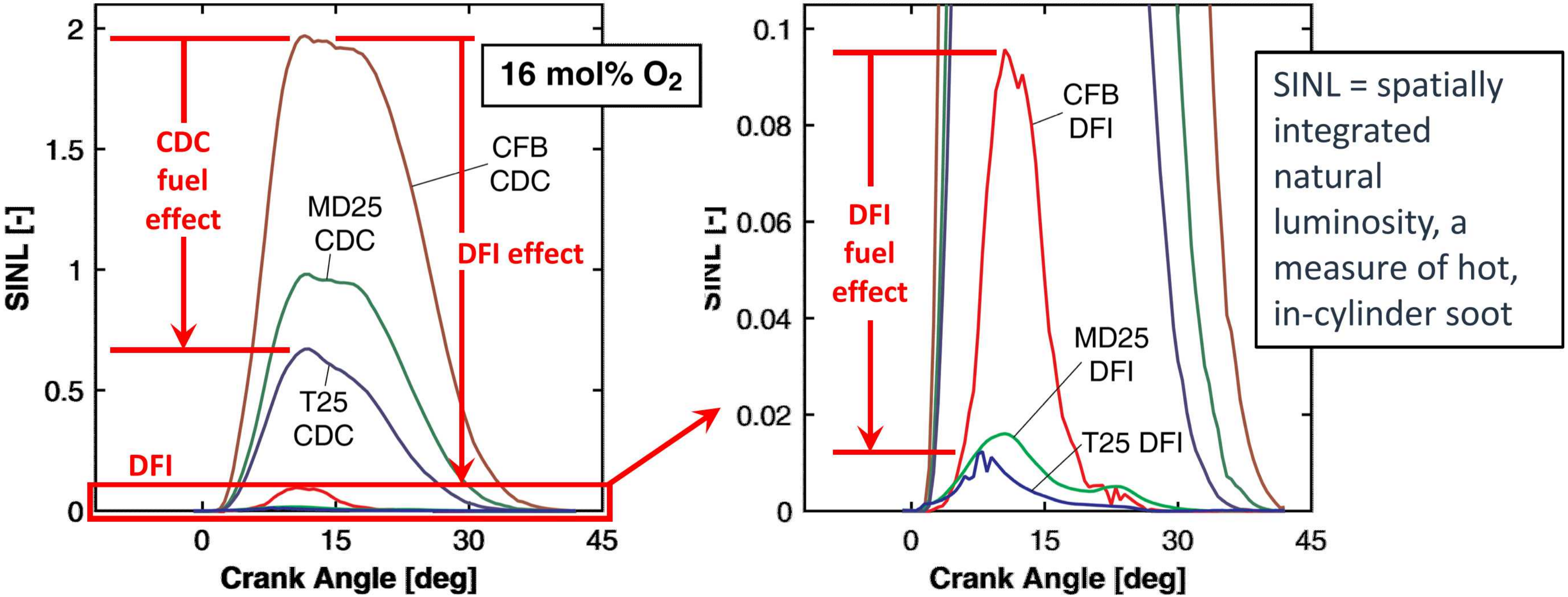


$$\phi_{\Omega,T25} = 36.3$$

- **Two (2) dilution levels: 16 & 21 mol% $O_2$**
- **Two (2) combustion strategies: DFI vs. CDC**



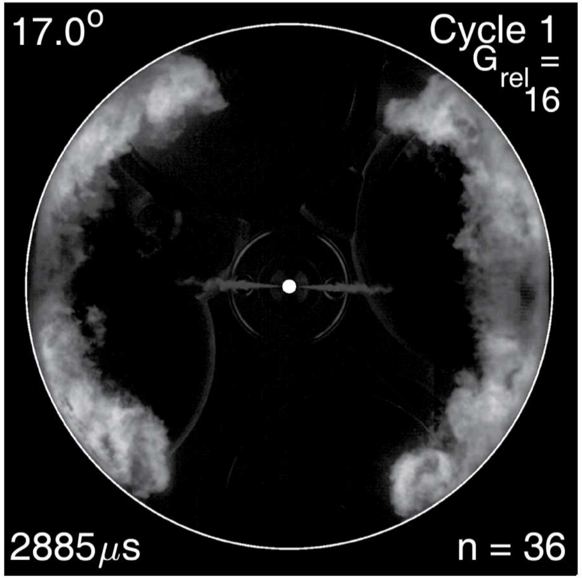
# 3. DFI is synergistic with oxygenated renewable fuels, lowering SINL by another 10X relative to petro-diesel.




- Changing from CDC to DFI lowers SINL more than adding 25 vol% of either oxy.
- Fuel effect is larger for DFI than for CDC (on a percentage basis)

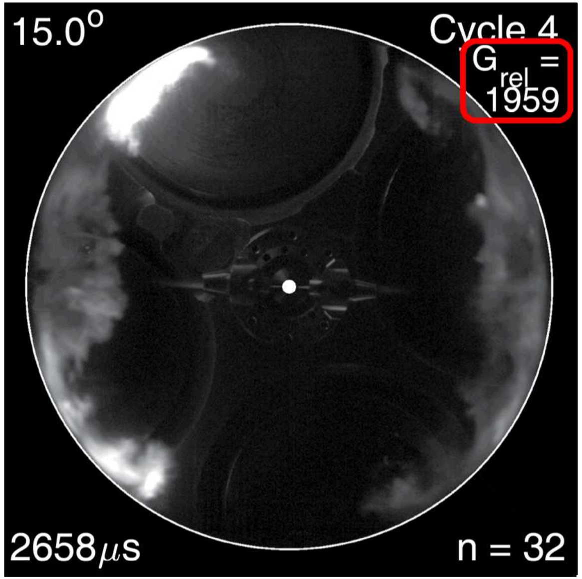
# Fuel oxygenation & DFI together can curtail SINL by ~100X on average, often preventing soot formation.

**CFB CDC @ 16 mol% $O_2$**



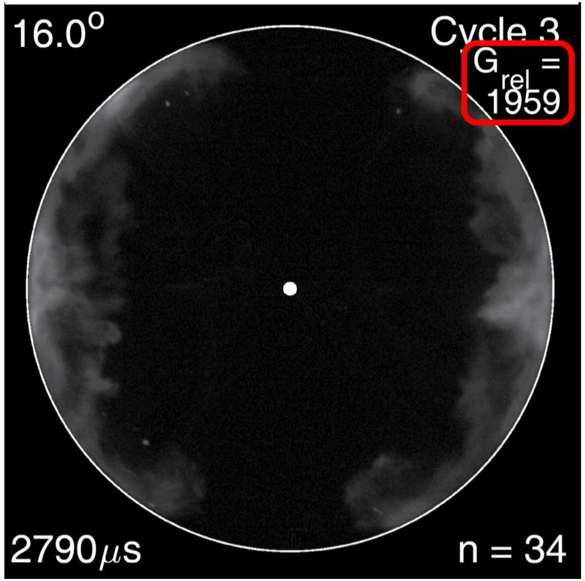

**Status quo:**
**Significant engine-out soot**

**MD25 DFI @ 16 mol% $O_2$**




**Transition:**
**"Zero" engine-out soot**

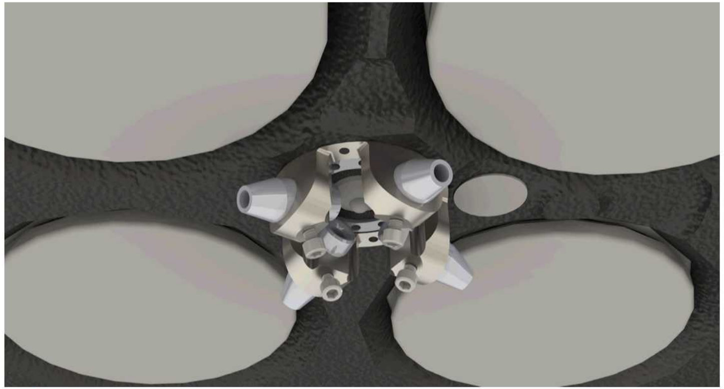
**T25 DFI @ 16 mol% $O_2$**




**Leaner lifted-flame combust. (LLFC): "Zero" in-cyl. soot**

# 4. DFI is viable over a range of operating conditions with conventional diesel fuel.

| | |
|---|---|
| Engine speed | 1200 rpm |
| Load (gross IMEP) | 2.4 – 8.7 bar |
| Fuel | No. 2 S15 cert. diesel |
| Injector tip | 4 × 0.108 mm × 140° |
| Injection pressure | 80, **180**, 240 MPa |
| Intake-$O_2$ mole fraction | 12, 14, **16**, 18, 21% |
| Inj. duration (commanded) | 1.5, 2.5, **3.5**, 4.5 ms |
| Start of combustion timing | -5.0, **0.0**, +5.0 CAD ATDC |
| Intake manifold abs. press. | 2.0, **2.5**, 3.0 bar |
| Intake manifold temperature | 50, 70, **90** °C |
| Coolant temperature | 50, 70, **90** °C |
| Fired cycles per run | 180 |
| Runs per condition | ≥ 3 |



**4D2L12G3δ duct configuration**

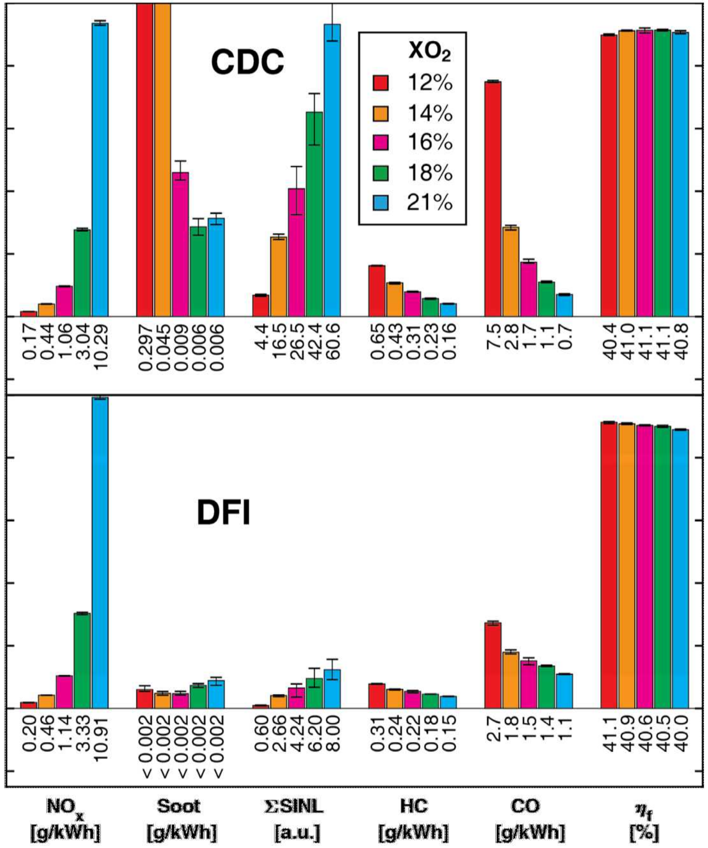
**Roughly corresponding to:**

- 1.3, **1.6**, 2.0 bar
- 13, 31, **49** °C

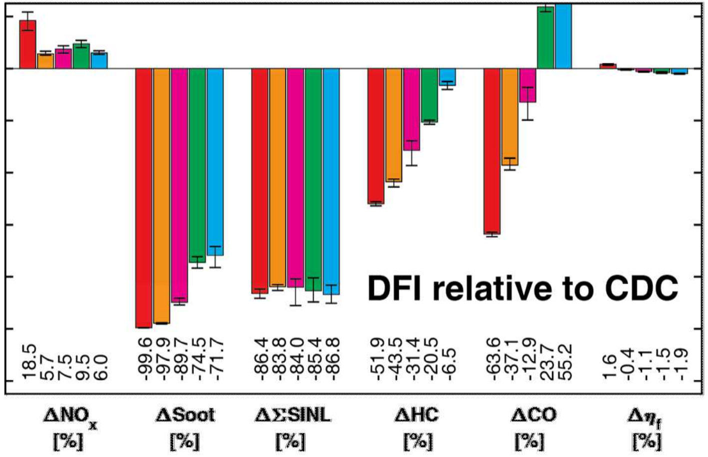
**in a metal engine with 17:1 CR**

# DFI exhibits generally lower emissions than CDC; DFI & CDC have similar efficiencies.

- DFI has lower soot, HC, & CO emissions at $XO_2$ levels where it is likely to be used
- $NO_x$ is much lower for DFI at min. feasible $XO_2$
- DFI $\eta_f$ (fuel-conv. efficiency) ↑ as $XO_2$ level ↓

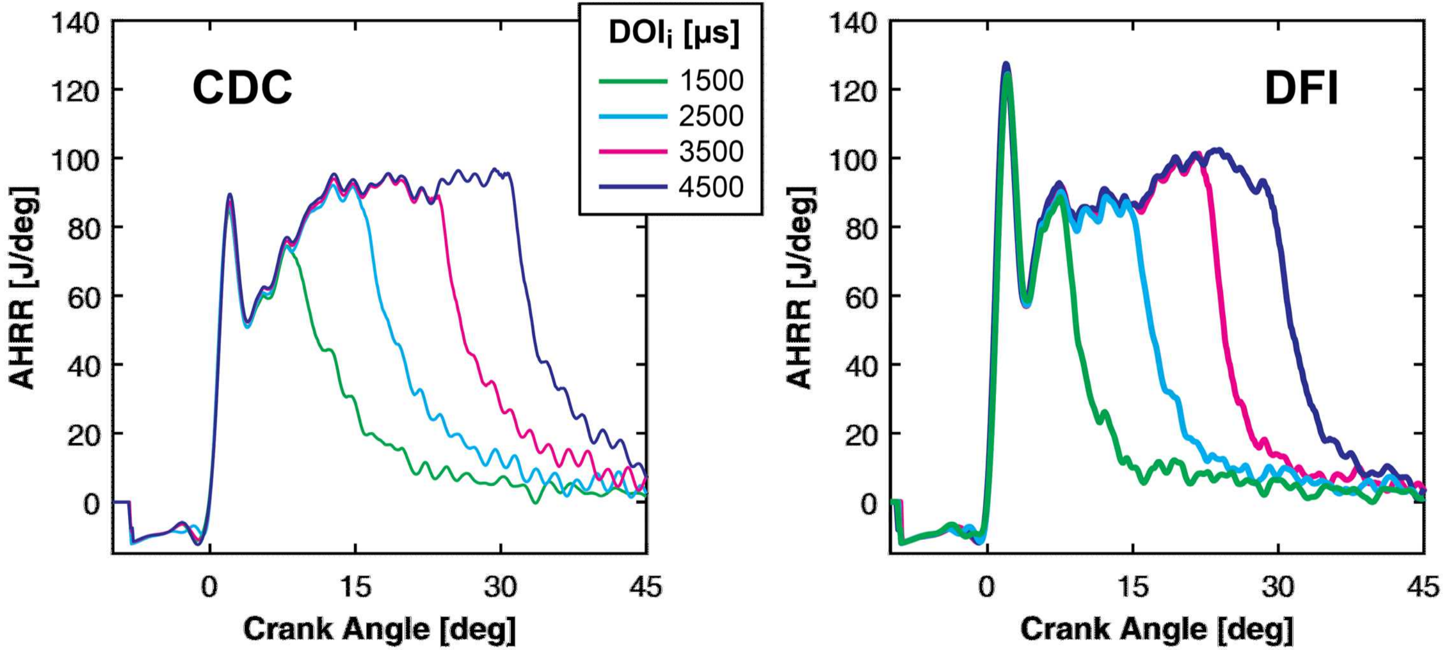



1200 rpm
~6.7 bar $IMEP_g$




$XO_2$ = intake-oxygen mole fraction

# DFI is easy to control, & its heat release is similar to CDC.




1200 rpm
2.4 - 8.7 bar $IMEP_g$

$IMEP_g$ = gross indicated mean effective pressure

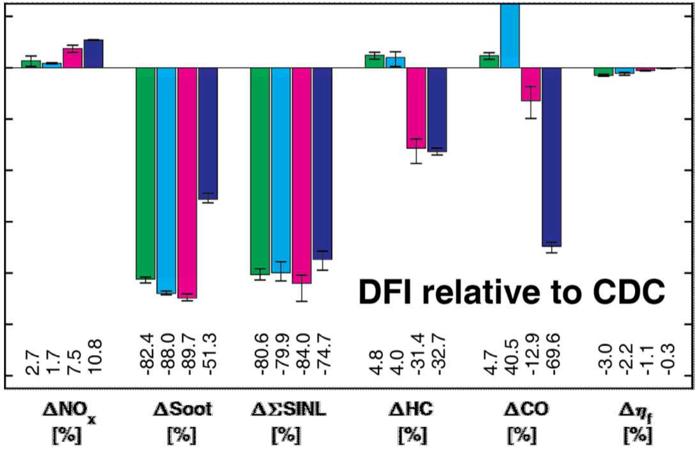
- $DOI_i$ = indicated (i.e., commanded) duration of injection
- DFI has larger premixed burns & shorter combustion durations than CDC

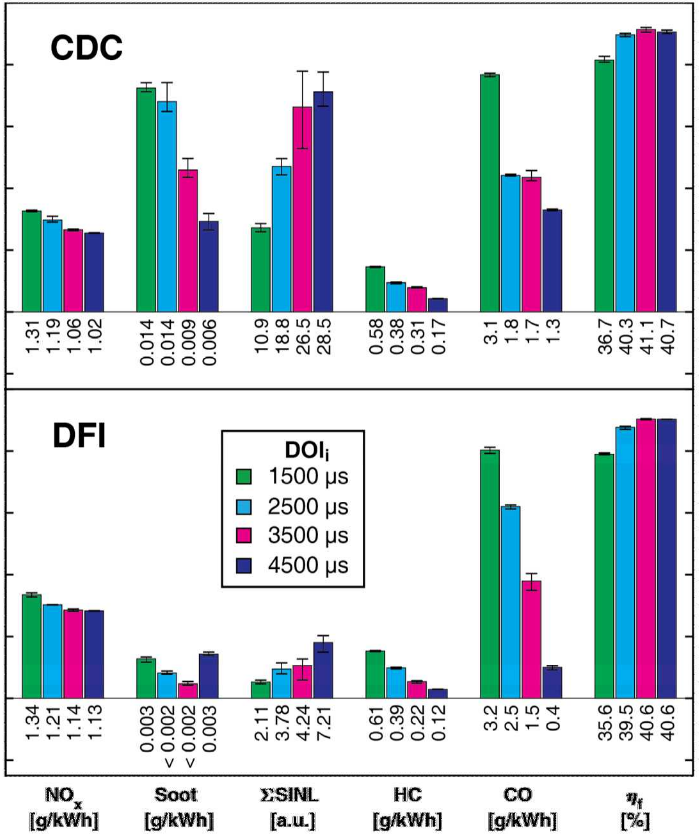
# DFI performs well across a range of loads.

- **Soot is 50 - 90% ↓ for DFI across the sweep**
- **$NO_x$ is 2 - 11% ↑ & $\eta_f$ is 0.3 – 3.0% ↓ for DFI**
  - Both can be improved via dilution
- **HC & CO are lower for DFI when $DOI_i$ is longer**
- **DFI performance generally ↑ with longer $DOI_i$**

**1200 rpm**
**2.4 - 8.7 bar $IMEP_g$**
**16% $XO_2$**

**$XO_2$ = intake-oxygen mole fraction**

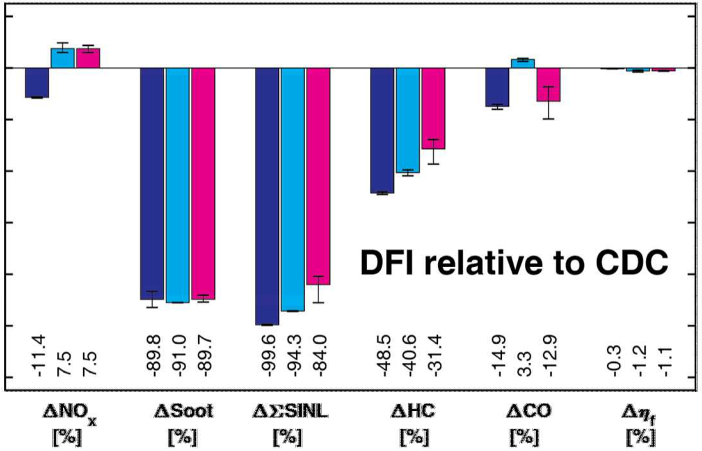


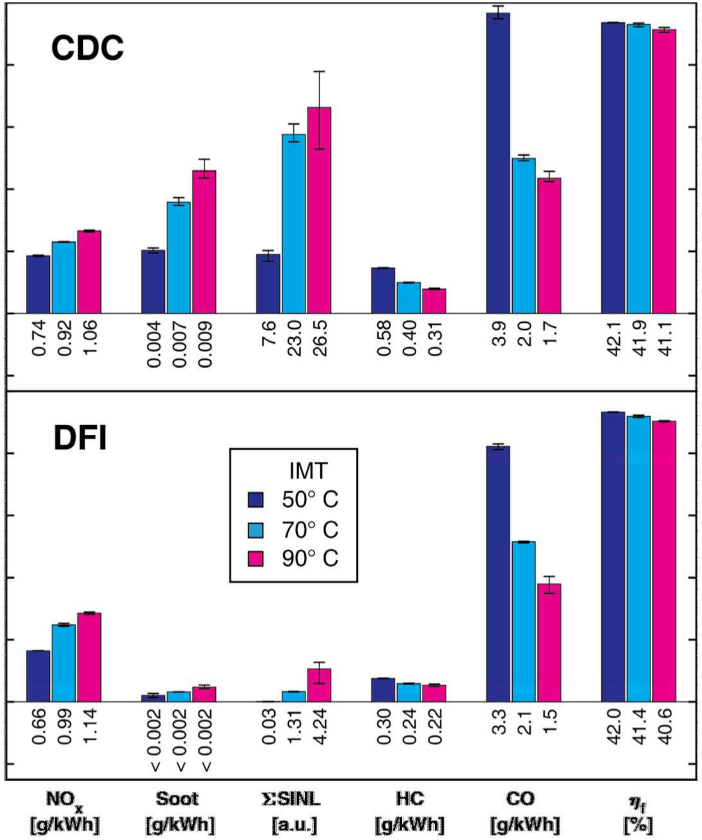



# DFI outperforms CDC at simulated cold-start conditions.

- DFI has lower soot & HC emissions
- DFI has lower or similar CO emissions
- $NO_x$ is lower for DFI at min. intake-manifold temperature (IMT)
- Similar $\eta_f$s for CDC & DFI

1200 rpm
6.7 – 7.0 bar $IMEP_g$
16% $XO_2$



# Conclusions

- **Ducted fuel injection (DFI):**
  - Is conceptually simple
  - Dramatically curtails soot production in engine experiments
  - $NO_x$ can be controlled via dilution without excessive soot
    - Breaks the soot/$NO_x$ trade-off with dilution
  - Is fully compatible with conventional diesel fuel
  - Is synergistic with oxygenated renewable fuels
  - Exhibits generally lower HC & CO emiss. than CDC, & similar fuel-conv. efficiencies
  - Is viable over a range of operating conditions

**DFI with oxygenated, renewable fuels provides a promising potential path to practical, clean, & sustainable vehicles & machines for the future.**

# Additional information on Sandia DFI research

- YouTube video for R&D 100 Special Recognition Silver Medal in "Green Tech": https://youtu.be/1dijtRUZeLw
- *Scientific American* article: https://www.scientificamerican.com/article/can-diesel-finally-come-clean/
- 1st paper in *Applied Energy*: https://www.sciencedirect.com/science/article/pii/S0306261917308644
- 2nd paper in *Applied Energy*: https://www.sciencedirect.com/science/article/pii/S0306261918307888
- 1st results from DFI engine experiments: https://saemobilus.sae.org/content/03-12-03-0021/
- Results from 4-duct parameter-sweep study will be presented at SAE WCX20