SAND2022-7870C

A Path Forward for Heavy-Duty Engine Applications: Ducted Fuel Injection with Sustainable Fuels

Charles J. Mueller, Christopher W. Nilsen, Gustav Nyrenstedt, Kirby J. Baumgard, Drummond E. Biles, Boni F. Yraguen, et al.
Sandia National Laboratories, Livermore, California

*Research supported by: **U.S. Dept. of Energy, Vehicle Technologies Office***
*Program managers: **Kevin Stork, Michael Weismiller, & Gurpreet Singh***

2022 University of Wisconsin Engine Research Center Symposium: Low-Net-GHG Fuel and Engine Technologies

Madison, Wisconsin

June 16, 2022

**“The great way is near, but we seek it far away.
The great way is easy, but we seek it in the difficult.”**

– Mencius

Outline

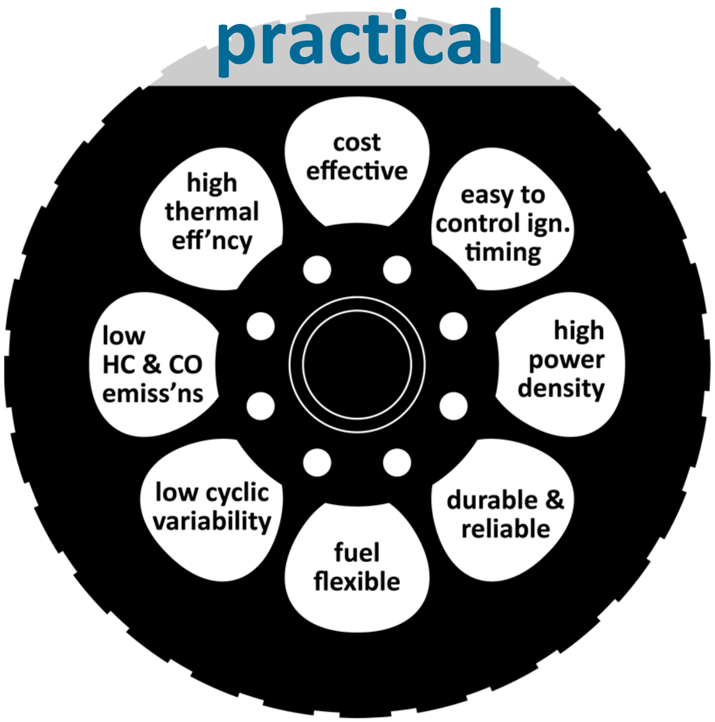
1. Background on ducted fuel injection (DFI) & fuel effects
2. Recent DFI results with low-net-carbon fuels
3. De-risking DFI for commercial applications

Time for Q&A after each part!

Part 1:
DFI & fuel effects background

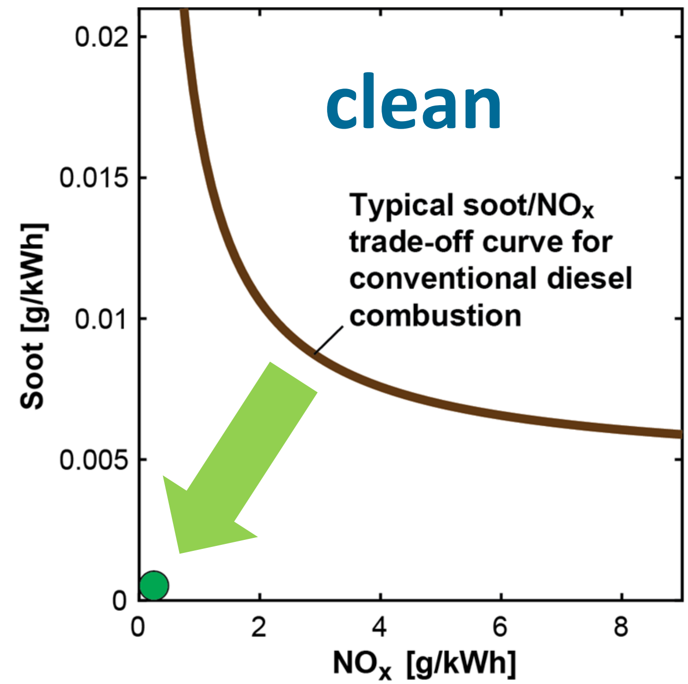
We need a pragmatic path for decarbonizing difficult-to-electrify applications.

Objective: Maintain all the desirable attributes of conventional diesel combustion…



+

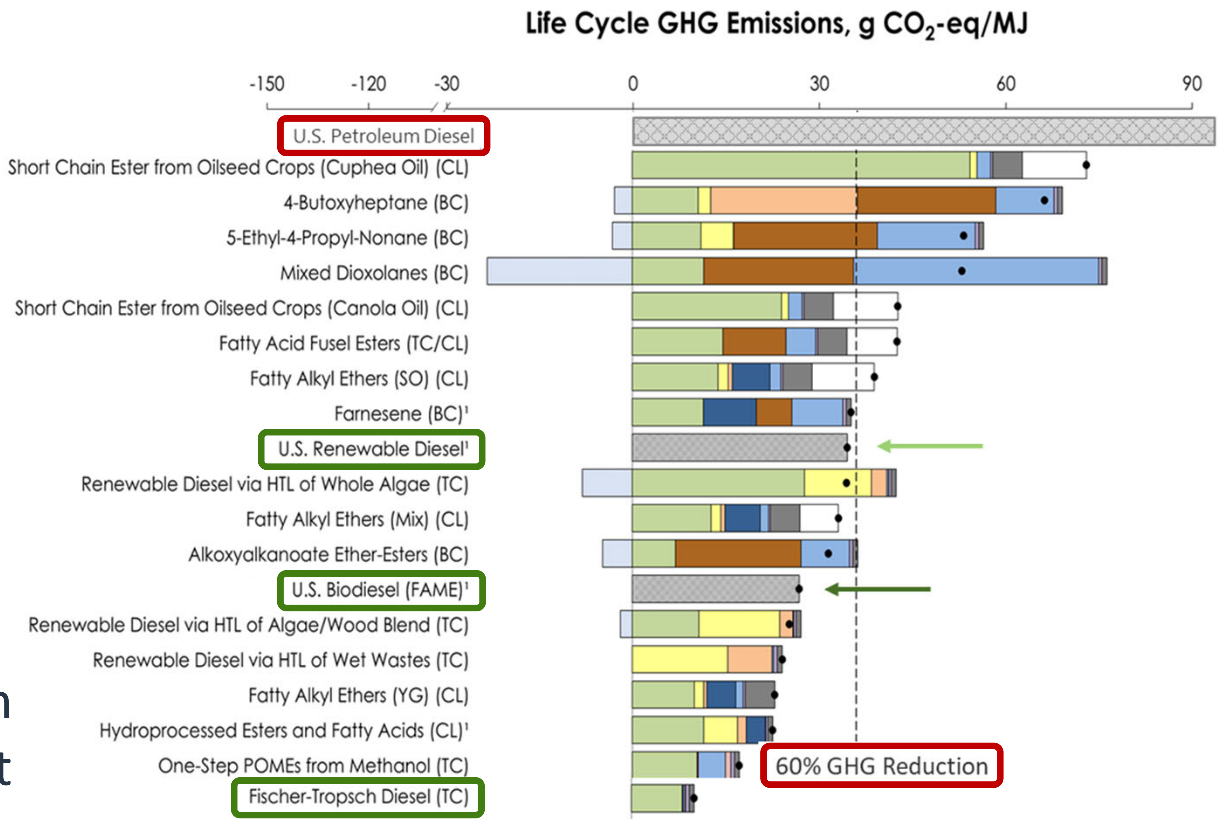
+



…while achieving net-zero carbon with home-grown fuels …with 10X – 100X lower soot & nitrogen oxides (NO_x) emissions.

At least several commercially viable, scalable, low-net-carbon fuel options exist in the diesel boiling range.

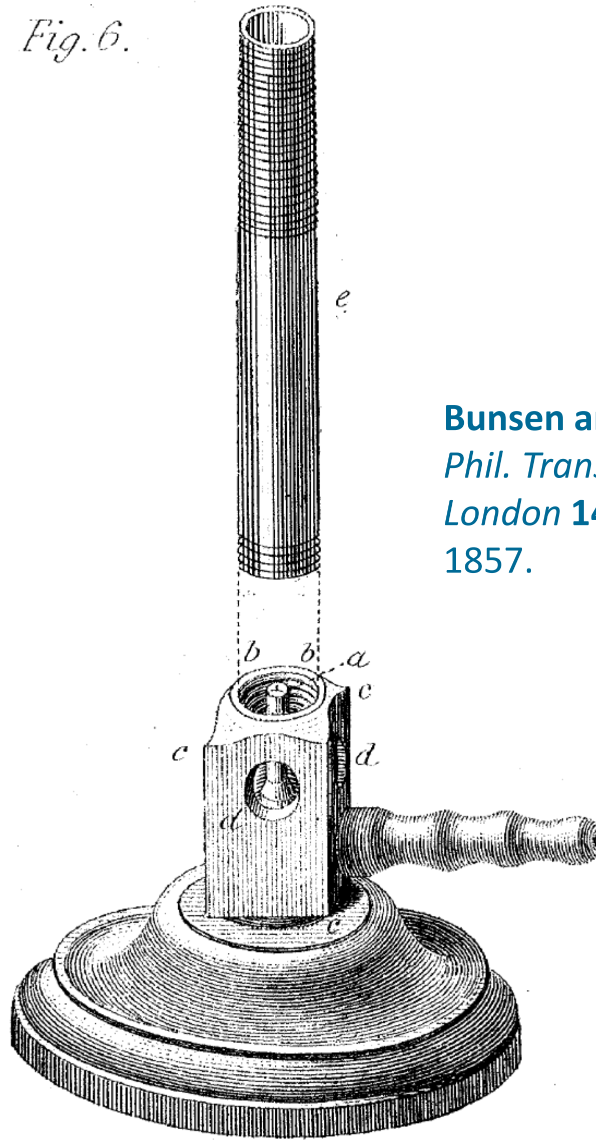
- **DOE-funded Co-Optimization of Fuels & Engines program addressed this**
- **Multiple blendstocks give >60% GHG reductions, e.g.:**
  - Renewable diesel
  - Biodiesel
  - Fischer-Tropsch diesel
- **But there's a problem…**
  - None of these blendstocks can provide 10X – 100X lower soot & NO_x emissions



Gaspar et al., PNNL Report 31421 (2021).

What is ducted fuel injection (DFI)?

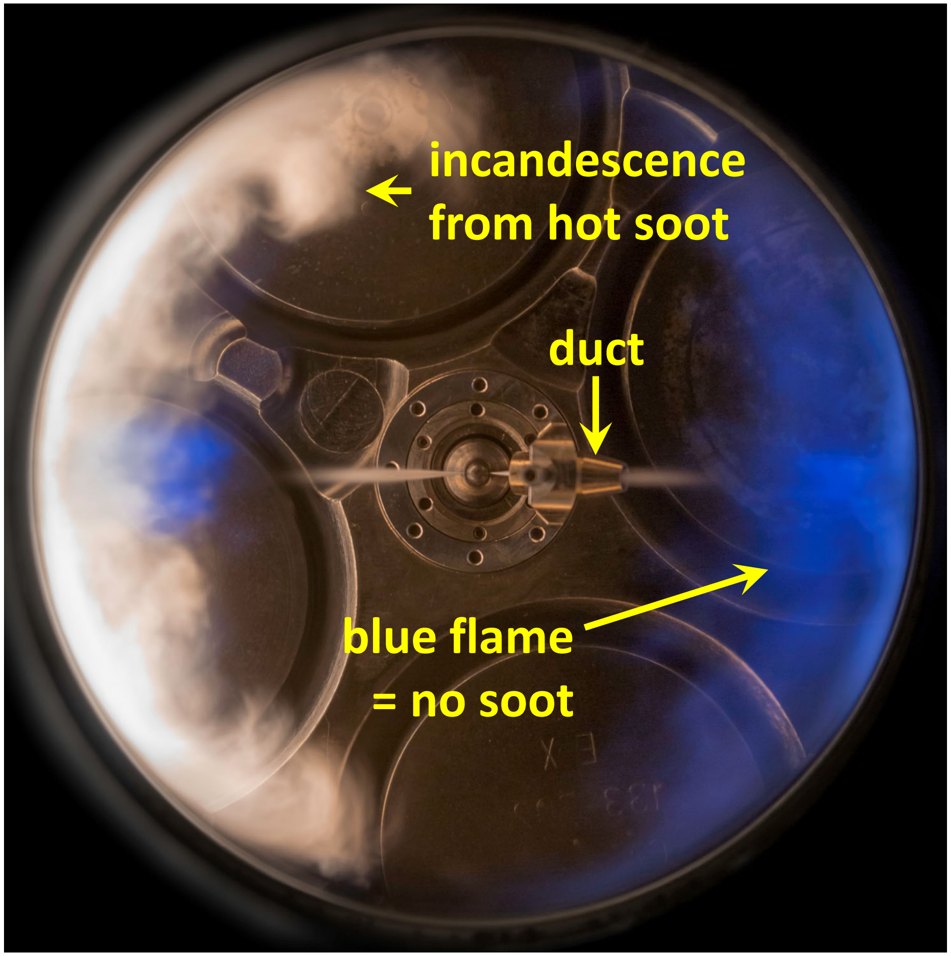
- **DFI is a simple, mechanical approach for improving diesel combustion**
  - Motivated by Bunsen burner concept



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

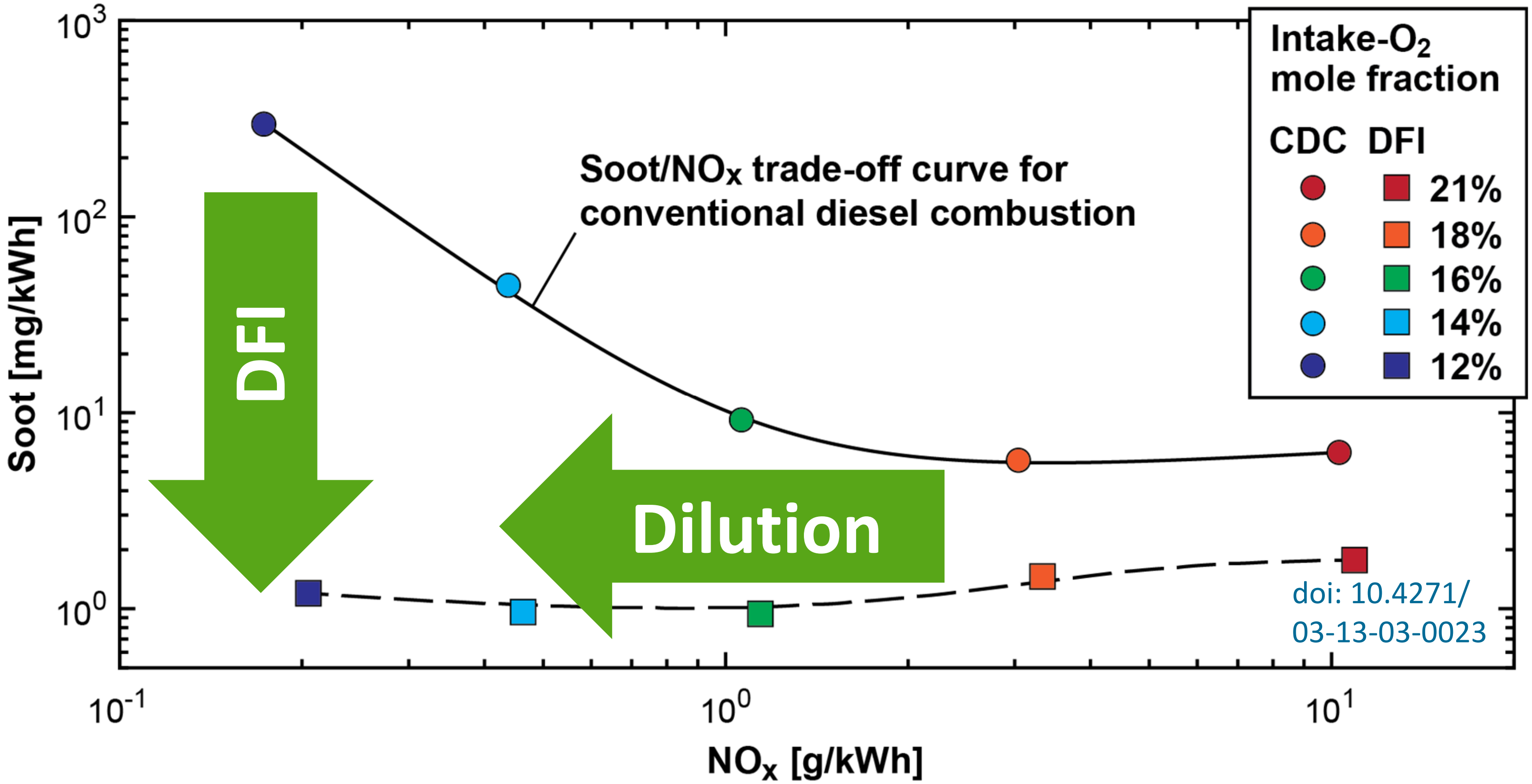
What is ducted fuel injection (DFI)?

- **DFI is a simple, mechanical approach for improving diesel combustion**
  - Motivated by Bunsen burner concept
- **Engine experiments have shown that DFI is effective at curtailing or even eliminating soot**



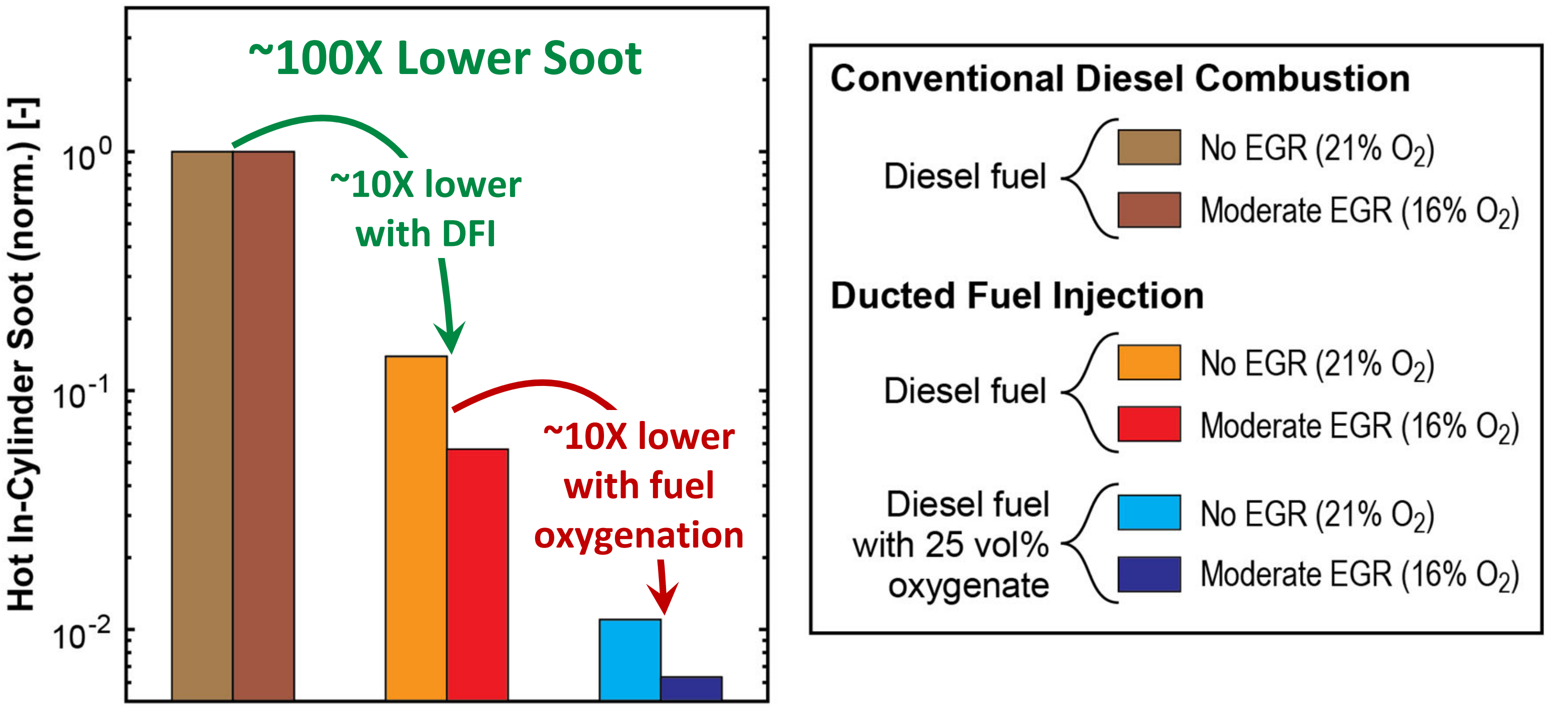
S. Ashley, https://www.scientificamerican.com/article/can-diesel-finally-come-clean/

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



*Optical-engine results for ~6.8 bar gross indicated mean effective pressure, 1200 rpm, steady state, 4-hole injector, No. 2 diesel fuel

In addition, DFI is synergistic with low-net-carbon, oxygenated & other renewable fuels.

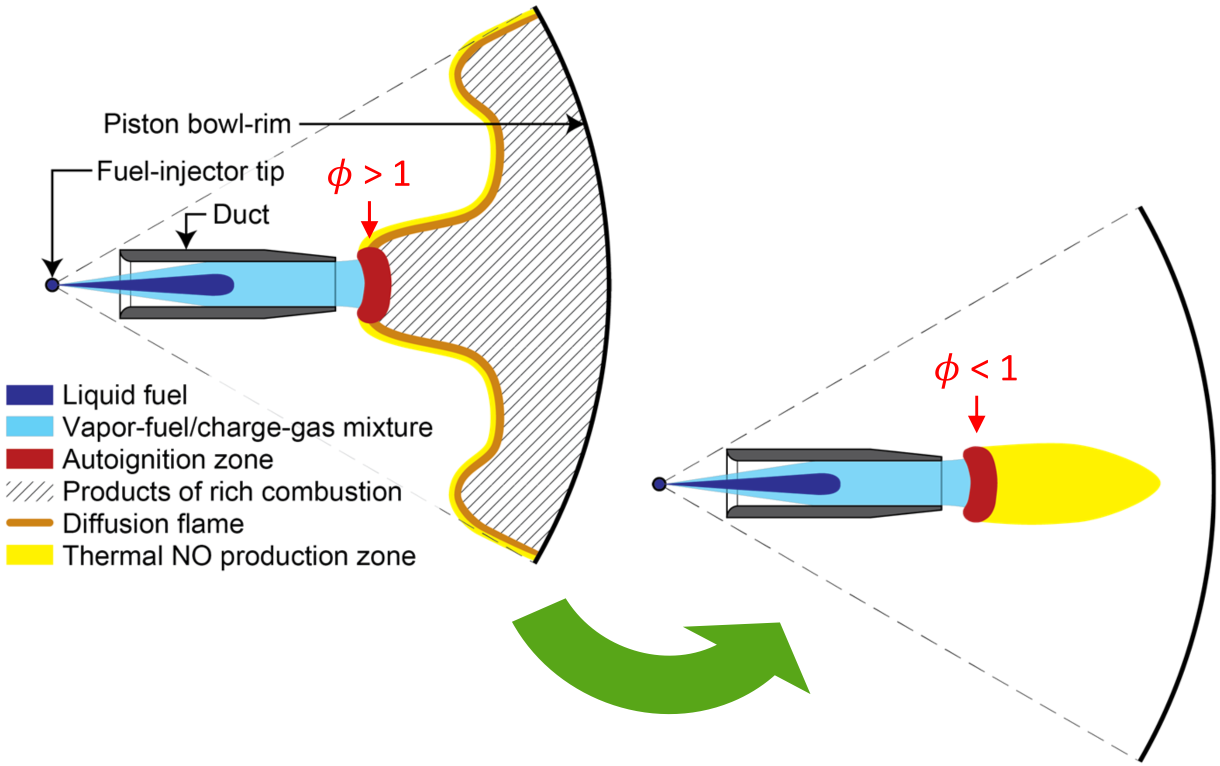


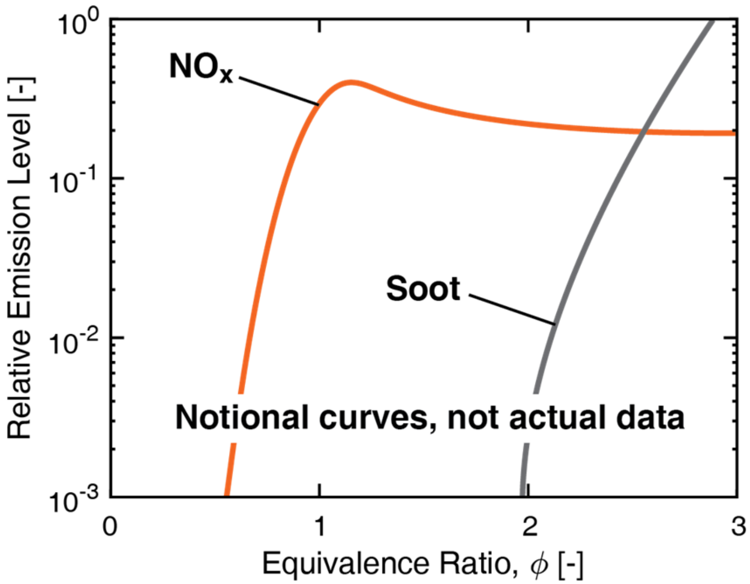
doi: 10.1016/j.jaecs.2021.100024

*Optical-engine results for ~2.6 bar gross indicated mean effective pressure, 1200 rpm, steady state, 2-hole injector

DFI could also enable low engine-out NO_x emissions without EGR.

- By making ϕ at the liftoff length < 1



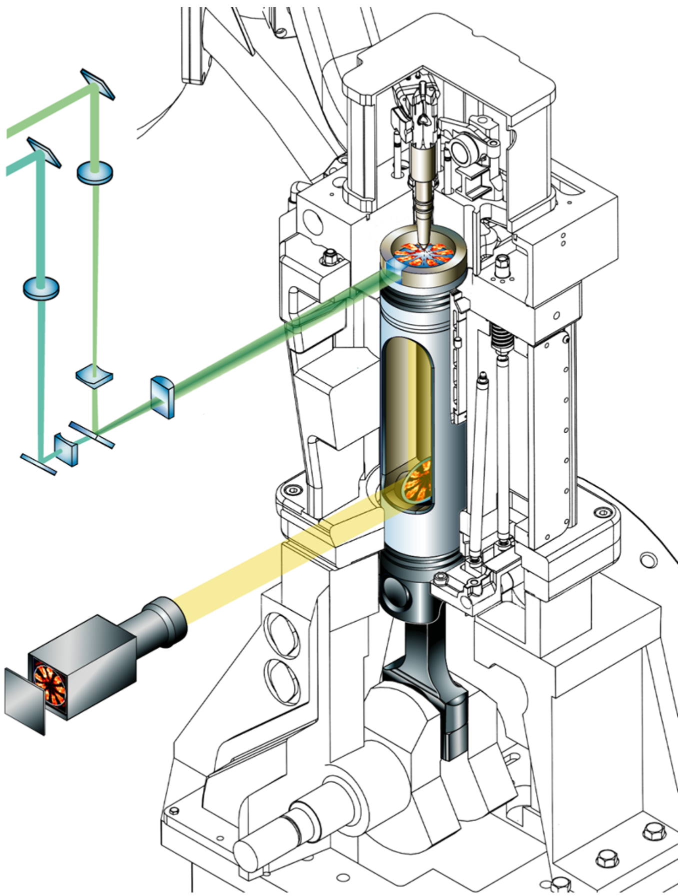


Part 1 summary

- **Changing to sustainable diesel fuels can help decarbonize difficult-to-electrify applications now**
  - But current sustainable diesel fuels alone can't break the soot/NO_x trade-off
- **DFI is a simple approach for enhancing mixing & curtailing engine-out soot**
  - Enables the use of cost-effective dilution/EGR to break the soot/NO_x trade-off
- **DFI is synergistic with oxygenated & other sustainable fuels**
  - Soot reductions are multiplicative
- **With further development, DFI could enable low engine-out NO_x emissions without dilution/EGR**

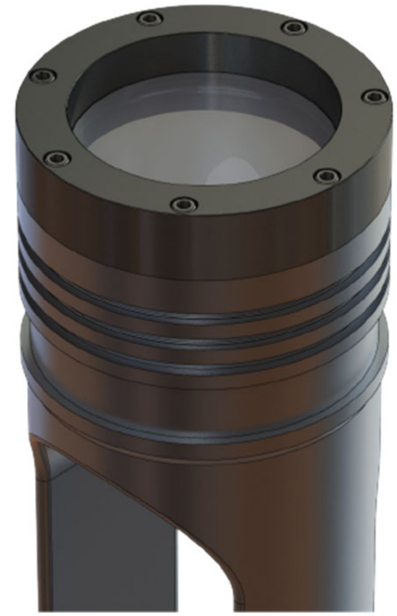
Part 2:
DFI results with low-net-carbon fuels

Sandia optical engine



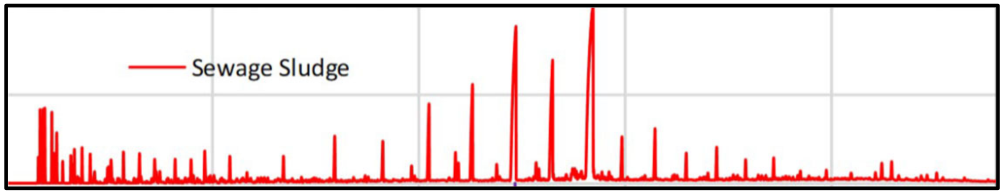
Research engine	Single-cylinder
Cycle	4-stroke CIDI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Displacement per cyl.	1.72 liters
Conn. rod length	225 mm
Conn. rod offset	None
Piston bowl diameter	90 mm
Piston bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio	0.59
Compression ratio	12.5:1
Simulated compr. ratio	17.0:1

- Cylindrical piston bowl with flat bottom



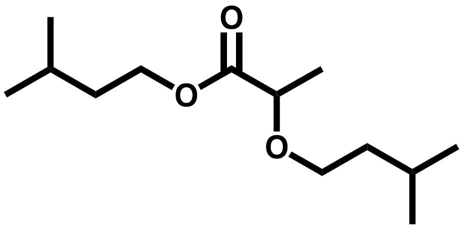
- Solenoid common-rail fuel injector

Fuels



- **Tested 4 fuels: Diesel, HEA00, HEA33, & HEA67**
  - Diesel = petroleum-based No. 2, S15 diesel certification fuel
  - HEA00 = sustainable diesel base fuel
    - 50 vol% from hydrothermal liquefaction of sewage sludge
    - 50 vol% from ethanol-to-diesel process (mixture of diesel-range iso-alkanes)
  - HEAxx = xx vol% alkoxyalkanoate (AOA) oxygenate blended with balance HEA00

	Diesel	HEA00	AOA
Cetane Number	46	>60	38.6-43.6
Specific Energy [MJ/kg]	42.92	43.7	32.05
Carbon Content [wt%]	86.8	85.3	67.8
Hydrogen Content [wt%]	13.2	16.3	11.4
Oxygen Content [wt%]	0	0.6	20.8
Density [kg/m^3 @ 20 °C]	843.7	785.5	887.2



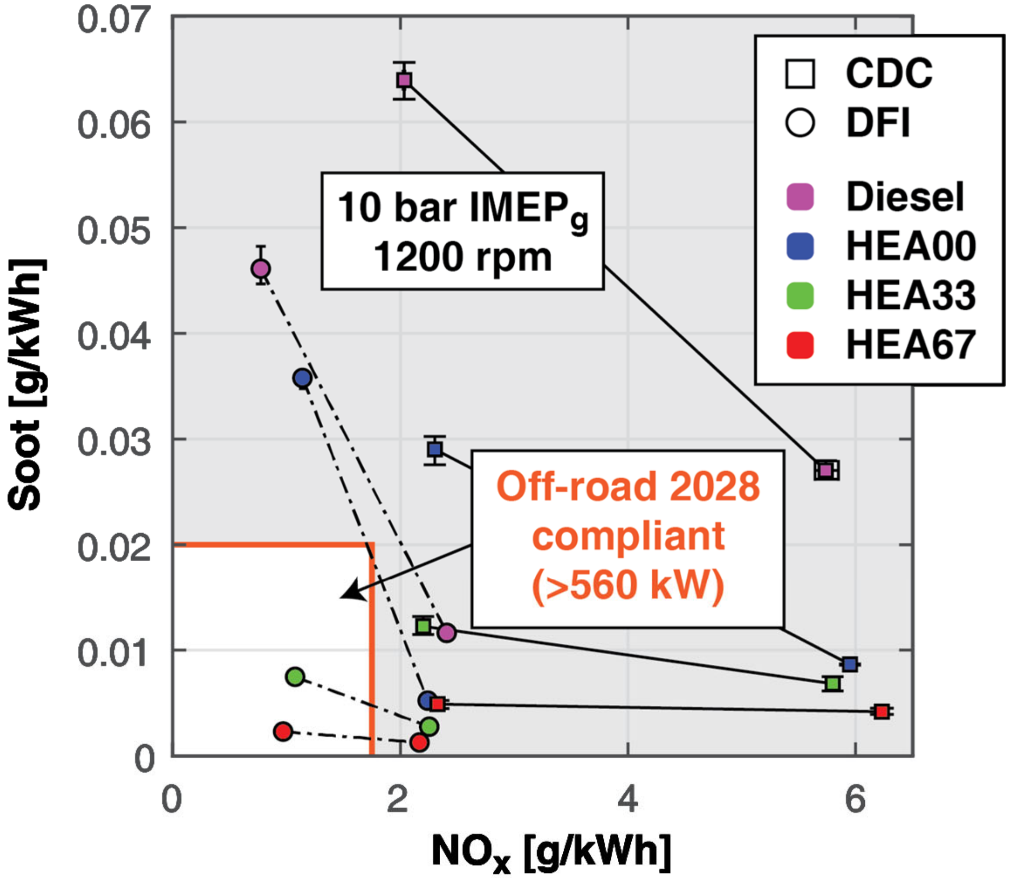
Operating conditions

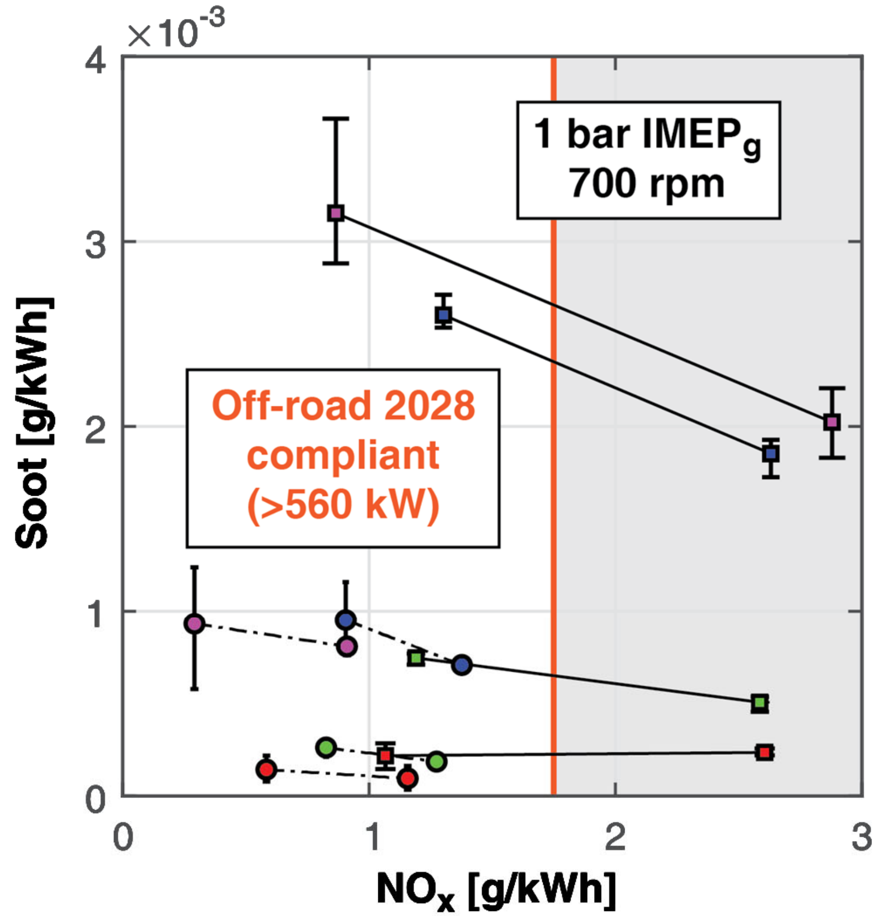
Description	Idle	Mid-load
Engine speed	**700 rpm**	**1200 rpm**
Load (gross IMEP)	**1.0 bar**	**10.0 bar**
Intake manifold abs. press.	1.5 bar	2.5 bar
Injection pressure	CDC: 80 MPa DFI: 60 MPa	180 MPa
Injector/duct configuration	4 × 0.173 mm × 140° / 4D3L12G3δ	
Intake-O_2 mole fraction	CDC: 16, 18, & 21% DFI: 14 & 16%	
Start of combustion timing	Maximum work timing	
Intake manifold temperature	90 °C	
Coolant temperature	90 °C	
Fired cycles per run	60	
Runs per condition	≥ 3	

Correspond to 0.98 & 1.6 bar in a 17:1 CR engine

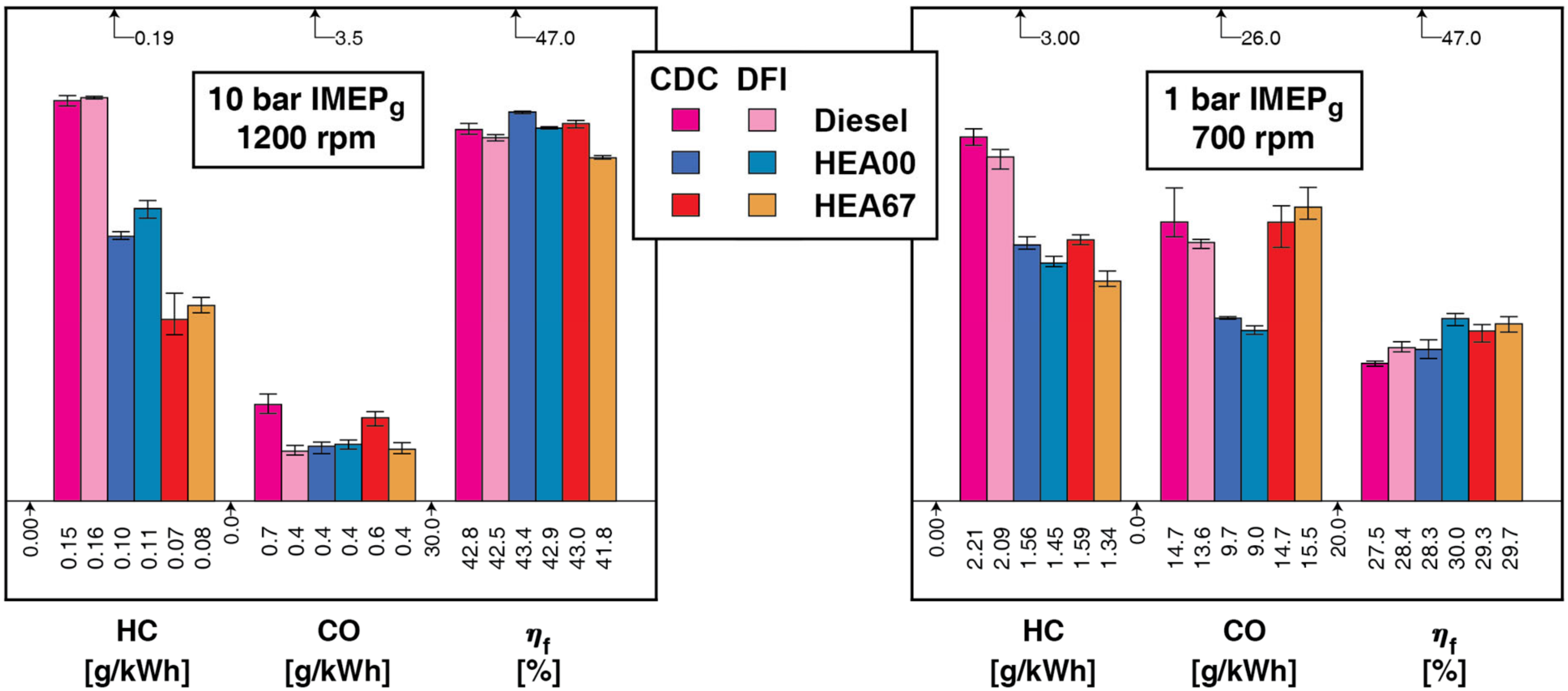
Corresponds to 49 °C in a 17:1 CR engine

HEAxx fuels + DFI + dilution enable significantly lower soot & NO_x at moderate load & idle





DFI has minor effects on HC & CO emissions as well as fuel-conversion efficiency.

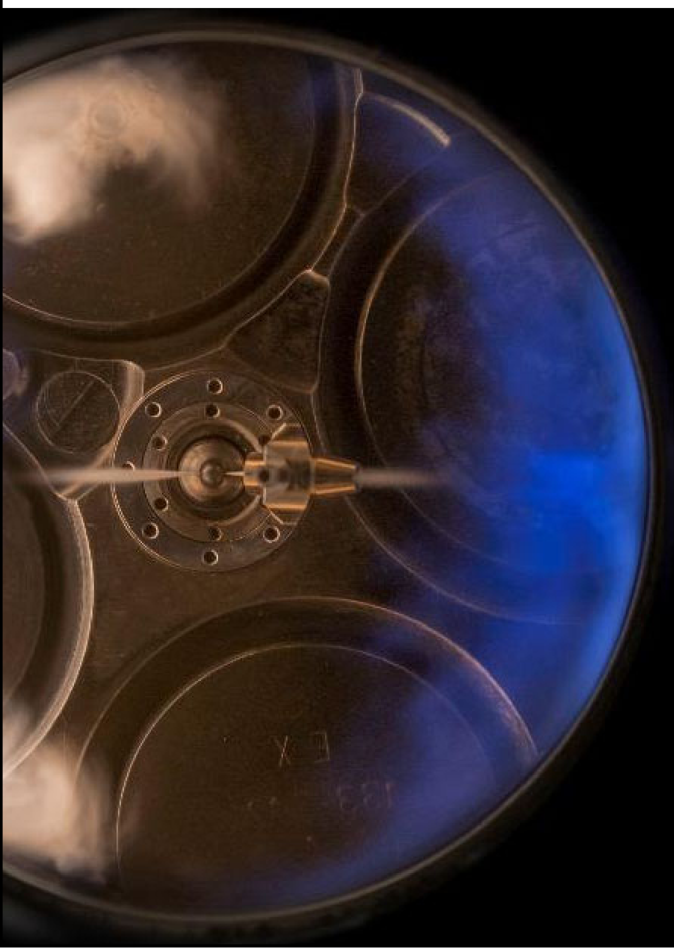


Part 2 summary

- **DFI with dilution can dramatically lower engine-out soot & NO_x emissions at idle & moderate loads**
  - Lessens demands on the aftertreatment system
- **Sustainable fuels with DFI enable additional reductions of engine-out soot, NO_x, & net-carbon emissions**
  - Might enable compliance with Tier 5 regs. without PM or NO_x aftertreatment
- **DFI has minor effects on HC, CO, & fuel-conversion efficiency**

Part 3:
De-risking DFI for commercial applications

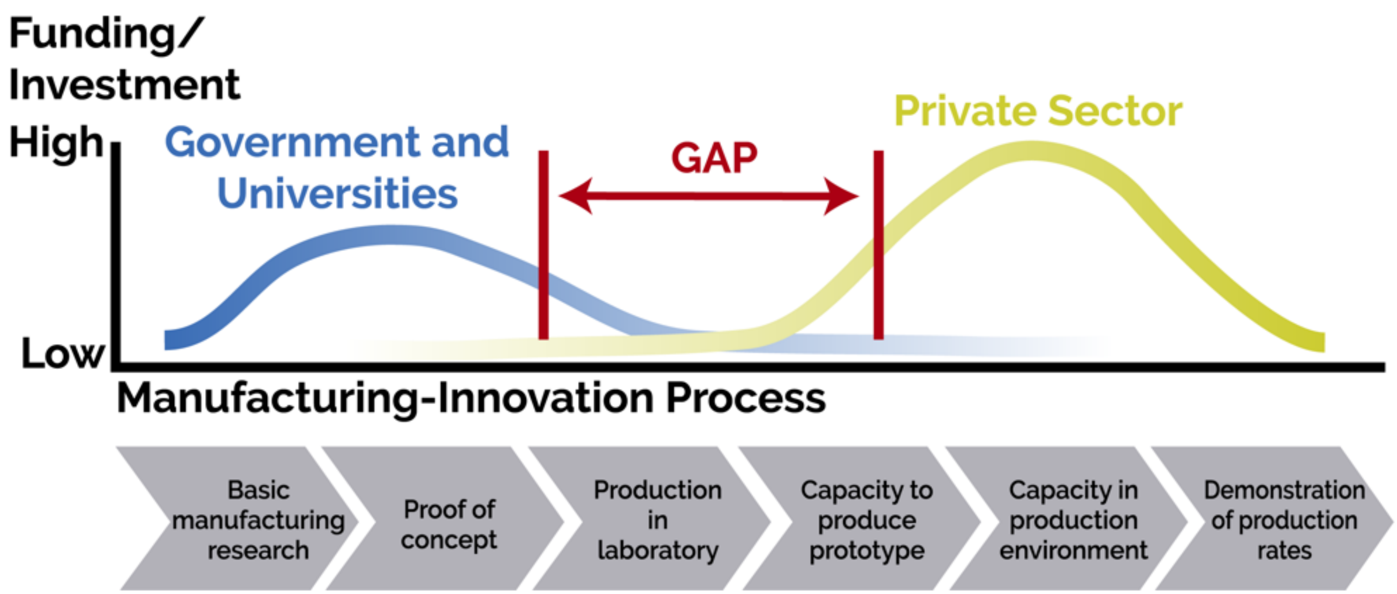
Objective



Advance DFI to a level where OEMs can successfully implement the technology in production.

Scope of work

- **Includes fundamental through applied tasks to bridge the "valley of death"**



- **"Consortium" approach**
  - Fundamental tasks are DOE-funded, applied tasks are industry-funded

High-level goals

1. Implement **DFI in a multi-cylinder engine** with production-viable hardware, showing an average of **at least 80% lower engine-out soot & NO_x emissions without an efficiency penalty** over steady-state & transient test cycles vs. conventional diesel operation.

2. Demonstrate the potential to achieve the above goal **while simultaneously reducing net-CO_2 emissions by at least 80%** vs. petroleum diesel fuel.

3. Provide **validated DFI modeling tools** to industry for in-house product-development efforts.

Part 3 wrap-up

- **Planned DFI commercialization project duration: 3 years**
- **Cost sharing: ~50/50 between DOE & industry**
- **Selected benefits:**
  - Strong leverage from close stakeholder collaboration
  - Learnings from 1st implementation of DFI in a multi-cylinder engine
  - Comparisons of performance & engine-out emissions datasets
    - For DFI vs. CDC, fossil diesel vs. low-net-carbon fuel, steady-state vs. transient
  - Improved understanding of DFI technology combustion-system integration, part cost, manufacturing, durability, operating costs, & certification
- **"Can my company still get involved?" Yes! Email cjmuell@sandia.gov for info.**

Take-away message

Ducted fuel injection + sustainable diesel fuels + dilution provides a pragmatic path to heavy-duty diesel engines with:

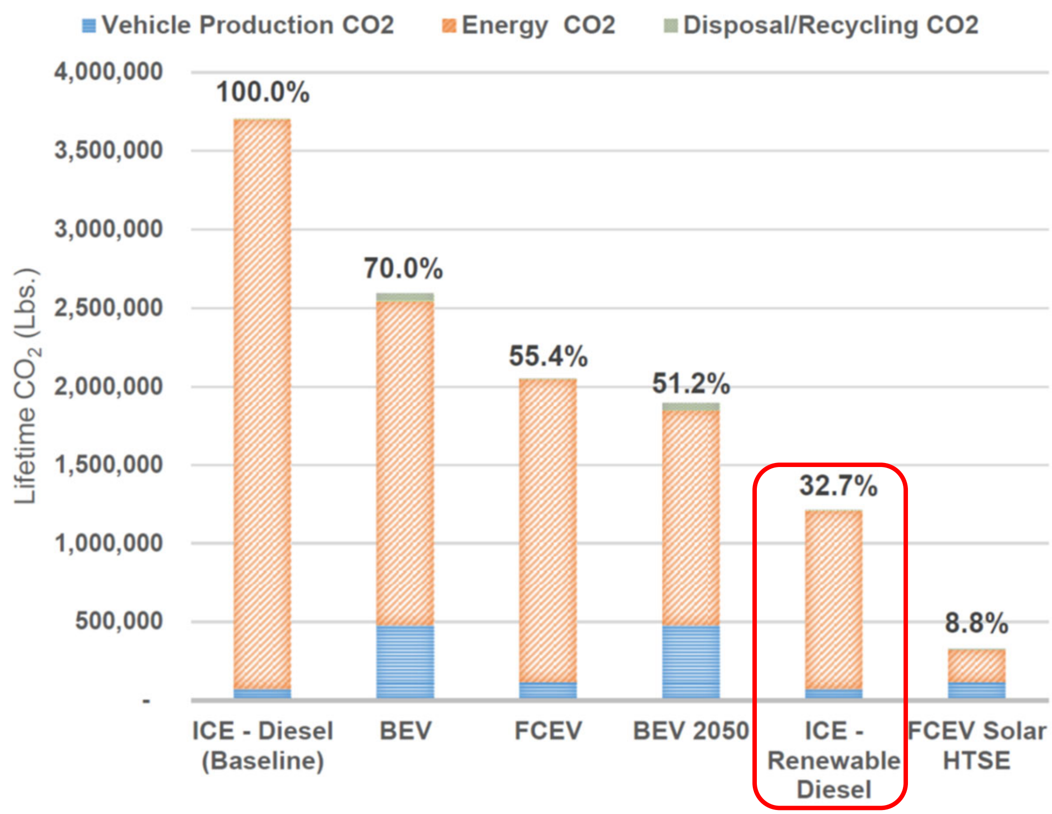
- at least 80% lower net-carbon emissions,
- at least 80% lower engine-out soot & NO_x emissions,
- no significant degradation in other emissions or efficiency relative to conventional diesel combustion,
- no massive investments in new infrastructure required,
- no widespread replacement of vehicles/machines required, &
- a small change to engine hardware needed.

A consortium has been formed to realize this vision within 3 years.

What are your thoughts?

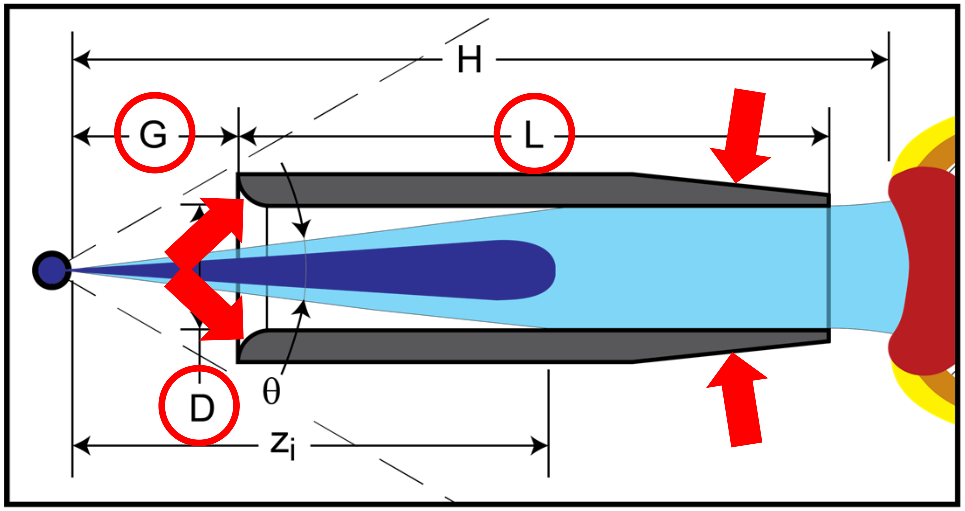
Additional information on Sandia DFI research

1. Initial DFI proof-of-concept experiments in constant-volume combustion vessel (CVCV, one-duct configuration): https://doi.org/10.1016/j.apenergy.2017.07.001
2. Investigating duct geometric parameter and operating-condition effects in CVCV (one-duct configuration): https://doi.org/10.1016/j.apenergy.2018.05.078
3. First DFI experiments in an engine (two-duct config., diesel fuel): https://doi.org/10.4271/03-12-03-0021
4. YouTube video for R&D 100 Special Recognition Silver Medal in "Green Tech": https://youtu.be/1dijtRUZeLw
5. Article in Scientific American: https://www.scientificamerican.com/article/can-diesel-finally-come-clean/
6. Engine operating-parameter sweeps (four-duct config., diesel fuel): https://doi.org/10.4271/03-13-03-0023
7. Non-reacting Reynolds-Average Navier-Stokes modeling of DFI: https://doi.org/10.4271/03-13-05-0044
8. Engine experiments at higher-load and idle conditions (four-duct configuration, diesel fuel): https://doi.org/10.4271/03-14-01-0004
9. Particle number and mass emissions of DFI: https://doi.org/10.1177/14680874211010560
10. Oxygenated/sustainable fuel effects on DFI: https://doi.org/10.1016/j.jaecs.2021.100024
11. Injector orifice diameter, duct length, and duct diameter effects: https://doi.org/10.1016/j.jaecs.2021.100030

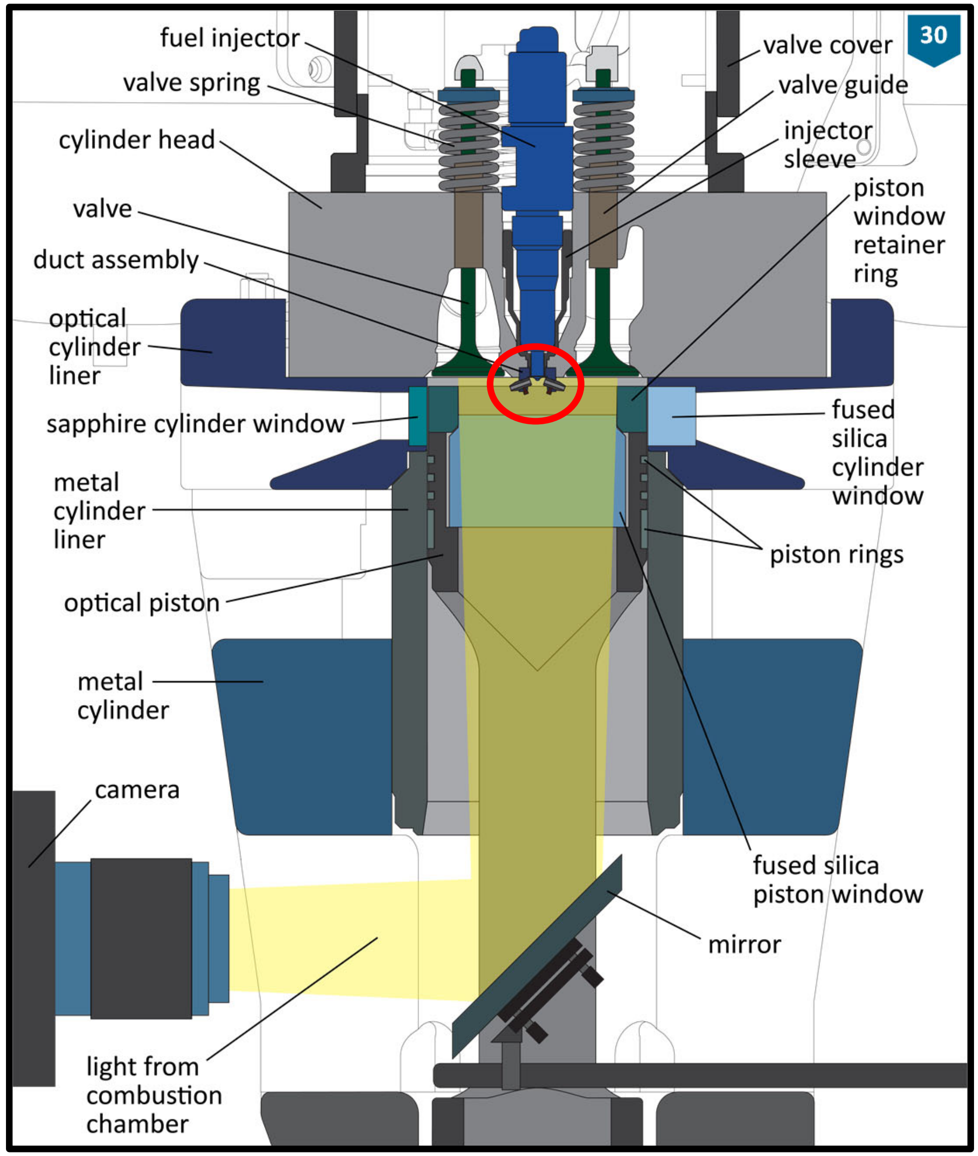


Short & Crownover, "Understanding the CO_2 Impacts of Zero-Emissions Trucks," American Transportation Research Institute, https://truckingresearch.org/, May 2022.

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)



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

Baseline operating-parameter values shown in bold teal text

Roughly corresponding to:

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

in a metal engine with 17:1 CR

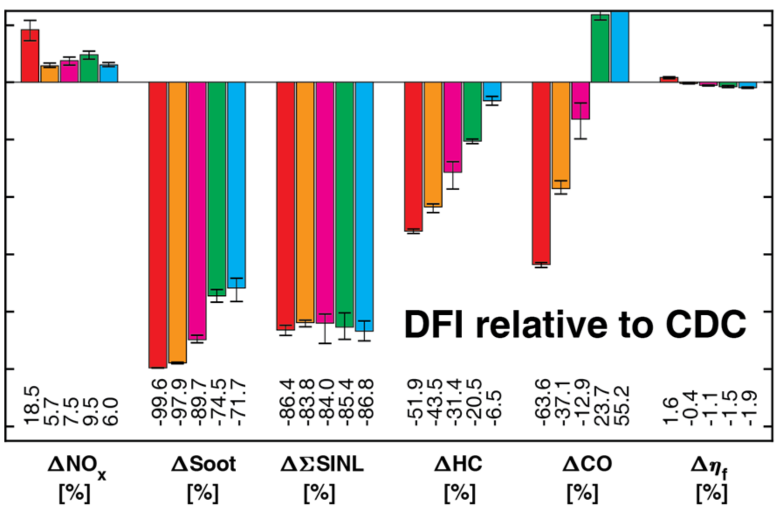
DFI is synergistic with dilution.

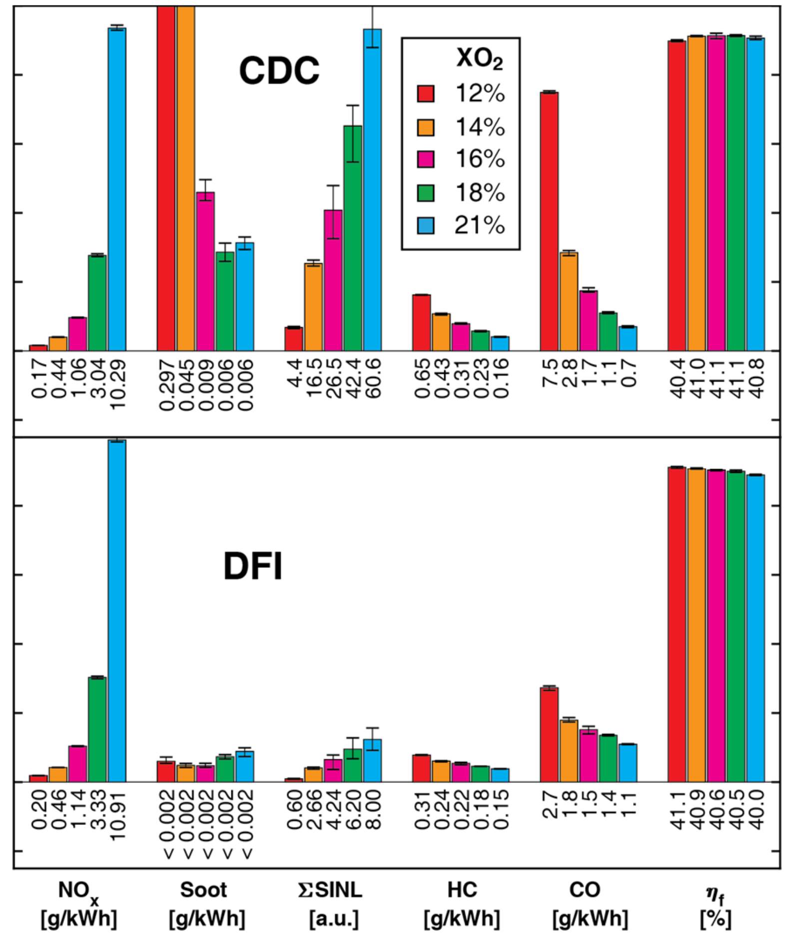
- **DFI shows generally lower emissions & higher efficiencies vs. CDC as dilution ↑. DFI has:**
  - Lower soot, HC, & CO emiss. at const. $XO_2 \leq 16\%$
  - Lower NO_x at minimum feasible XO_2 level
  - Higher fuel-conversion efficiency as XO_2 level ↓

XO_2 = intake-oxygen mole fraction

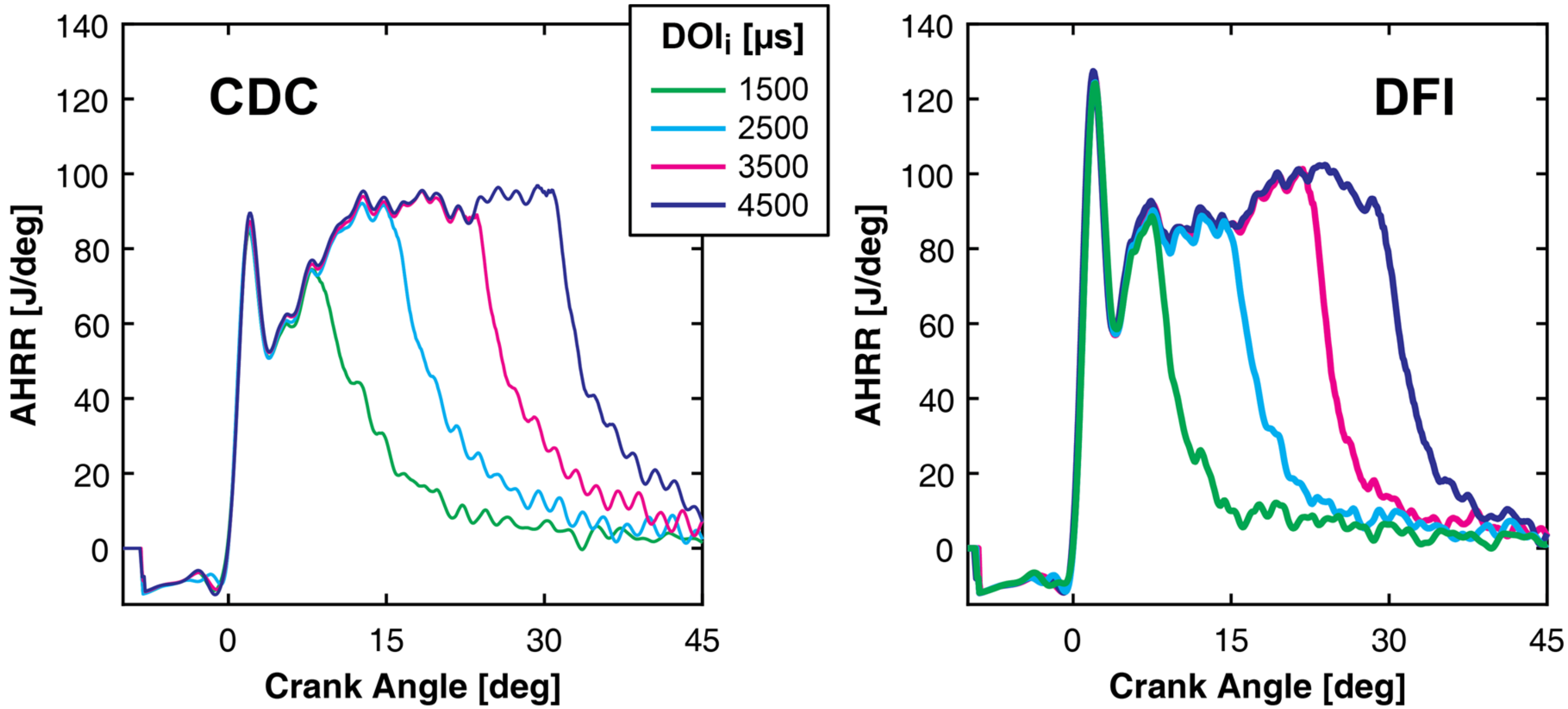
η_f = fuel-conversion efficiency

Four-duct config., 1200 rpm, ~6.7 bar $IMEP_g$, Diesel fuel





DFI is easy to control; its heat release is similar to CDC.



DOI$_i$ = indicated (i.e., commanded) duration of inj'n

Four-duct config., 1200 rpm, 2.4 - 8.7 bar IMEP$_g$, Diesel fuel

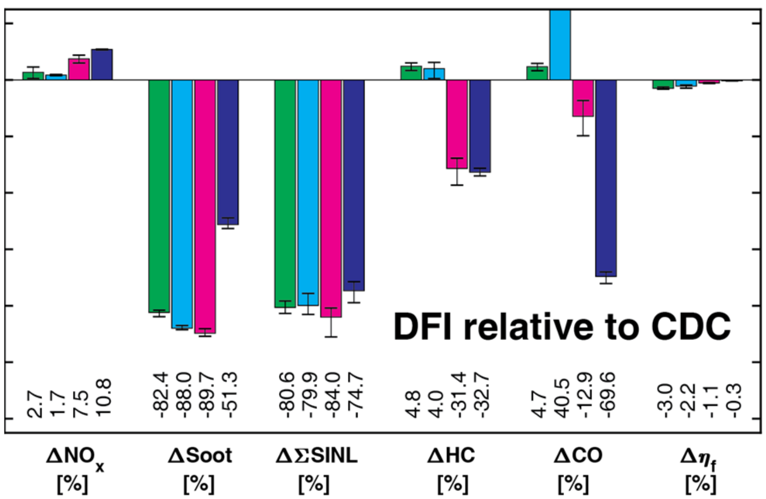
IMEP$_g$ = gross indicated mean effective pressure

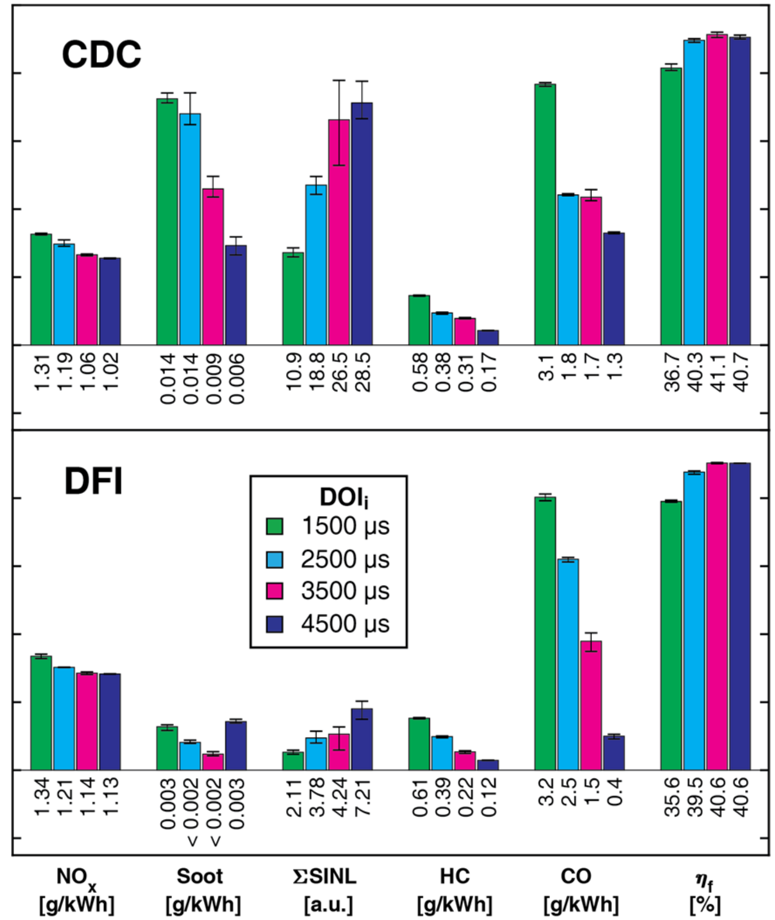
- Ignition timing & load are easily controlled by changing injection timing
- DFI has larger premixed burns & shorter combustion durations than CDC

DFI performs well across a range of loads.

- **Soot is 50 - 90% ↓ for DFI across the sweep**
- **NO_x is 2 - 11% ↑ & η_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**

Four-duct config.,
1200 rpm,
2.4 - 8.7 bar $IMEP_g$,
16% XO_2,
Diesel fuel

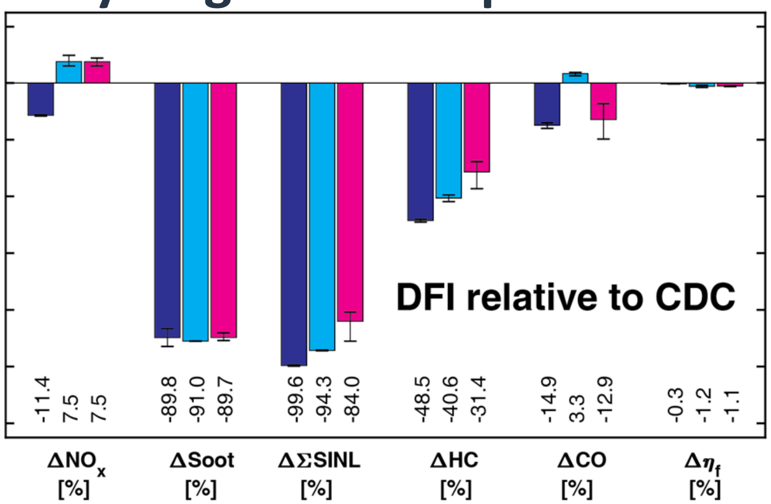


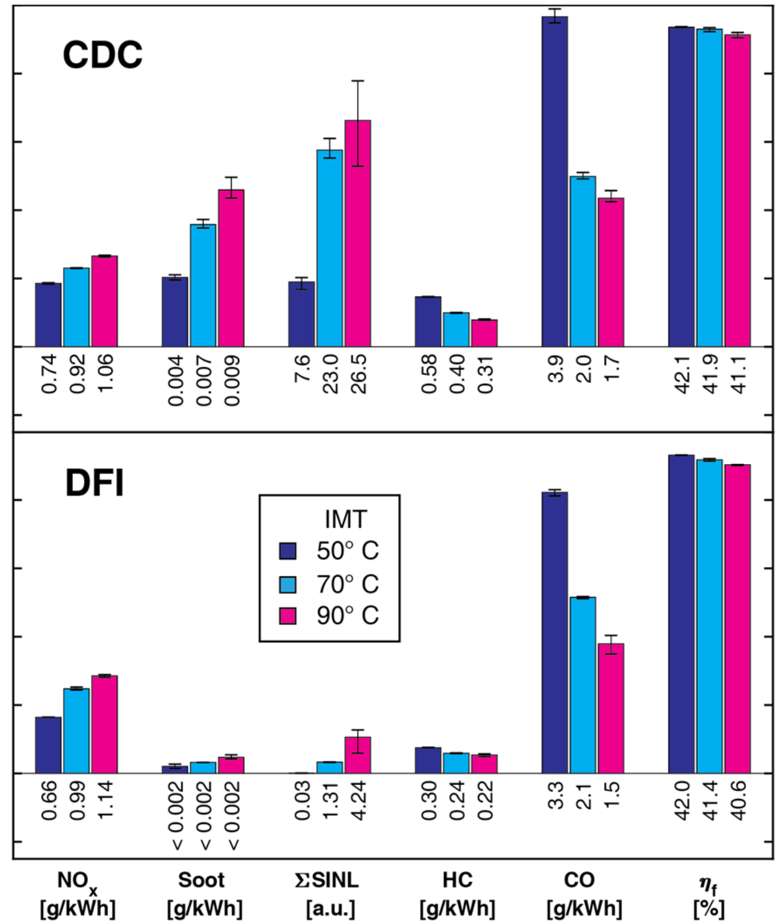


DFI outperforms CDC at simulated cold-start conditions.

- **Emissions & efficiency. DFI has:**
  - Lower soot, HC, & lower/similar CO
  - Lower NO_x at min. intake-manifold temp. (IMT)
  - Similar η_f vs. CDC
- **DFI should work well for cold-starts & at cond's below catalyst light-off temperature**

Four-duct config., 1200 rpm
6.7 – 7.0 bar $IMEP_g$
16% XO_2,
Diesel fuel

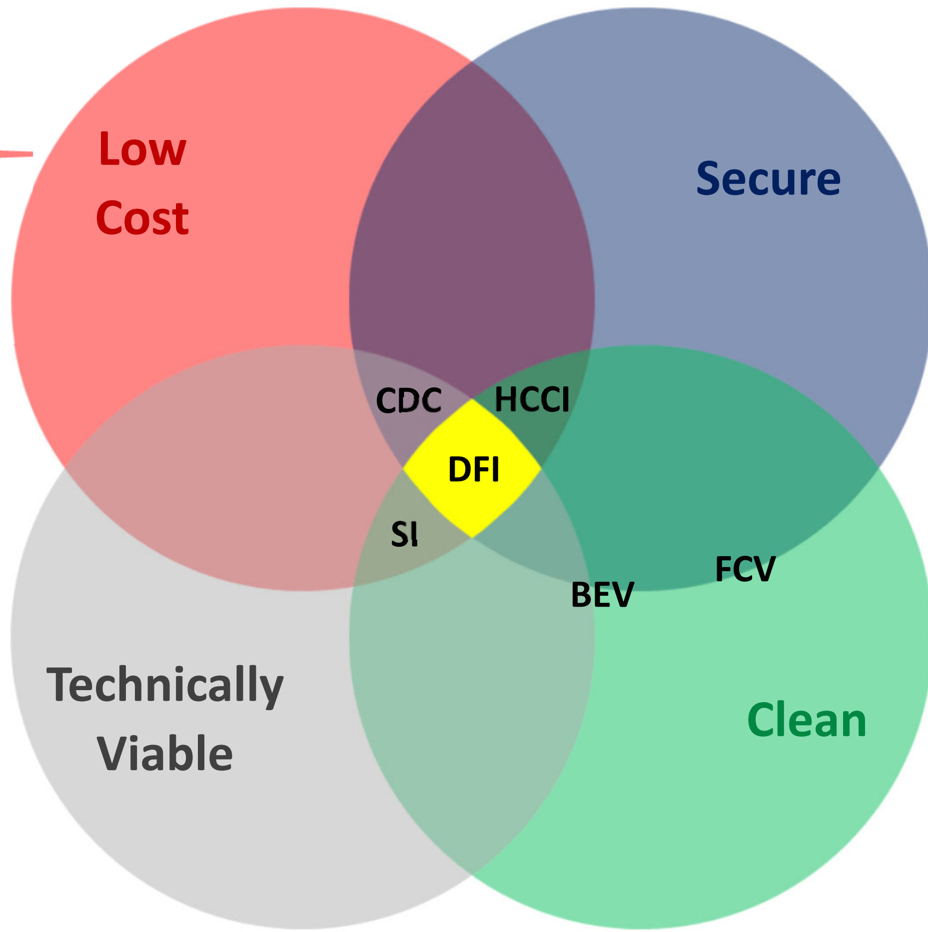




Conclusion: DFI with low-carbon fuels is a promising path to practical, clean, & sustainable ICE-powered machines.

- Maintains value of existing production facilities
- Compatible with existing fuels, energy-distribution infrastructure
- Uses abundant, inexpensive materials
- Lower DEF consumption, less costly aftertreatment
- Retrofittable

- High specific energy & power
- Easy to control ignition timing
- Fuel-flexible
- Wide speed/load range
- Low cyclic variability
- Durable & reliable



- High efficiency
- Energy security: compatible with domestic fuels/energy
- Climate security: synergistic with sustainable (oxygenated) fuels

- Low emissions of soot, NO_x, HC, & CO
- Reduces aftertreatment requirements
- Extends aftertreatment useful life, lessens regeneration/maintenance
- Less soot in lube oil