Ducted Fuel Injection (DFI) for Heavy-Duty Engines

Charles J. Mueller
Sandia National Laboratories
Engine Combustion Research Department
Livermore, California

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Program managers: ***Michael Weismiller*** *&* ***Gurpreet Singh***

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Overview

Timeline

- Project start: Oct. 1, 2018
- Project end: Sept. 30, 2019
- 56% complete

Budget

- FY19 funding: $550k
  - Mueller: $450k
  - Skeen: $100k
- FY18 funding: $0k

***Acronym definitions**: FY = fiscal year, runs Oct. 1 – Sept. 30; NO_x = nitrogen oxides; PI = principal investigator; MOU = Memorandum of Understanding; Co-Optima = Co-Optimization of Fuels and Engines program; CRADA = Cooperative Research & Development Agreement; **Next slide**: HC = hydrocarbon; CO = carbon monoxide*

Barriers

- "The research areas of highest priority for clean diesel combustion are:
  a. Reduced engine-out NO_x and particulate emissions
  b. …"

*from https://www.energy.gov/sites/prod/files/2018/03/f49/ACEC_TT_Roadmap_2018.pdf, Page 2.

Partners

- PI: Charles J. Mueller
- Co-Optima
- Caterpillar & Ford (CRADA)
- Advanced Engine Combustion MOU

Relevance

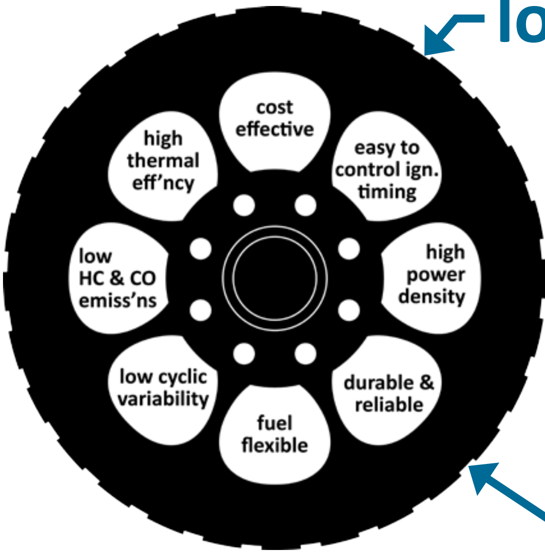
"The U.S. Department of Energy's Vehicle Technologies Office provides low cost, secure, and clean energy technologies to move people and goods across America." https://www.energy.gov/eere/vehicles/vehicle-technologies-office

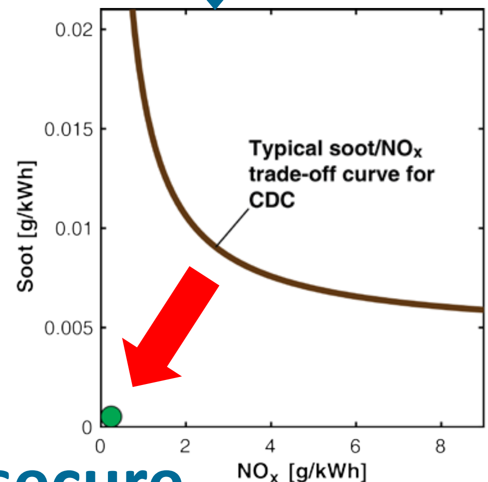
Our objective: Maintain all the desirable attributes of conventional diesel combustion (CDC)…

low cost

clean

Co-Optima (see FT077)





secure

…with 10X – 100X lower soot & NO_x emissions

…while harnessing synergies with domestically sourced fuels

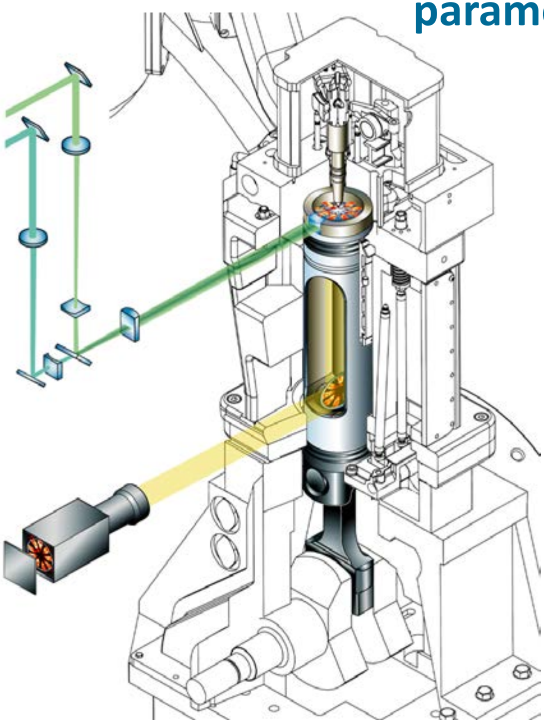
Milestones

- **Dec. 31, 2018: Install & align DFI two-duct holder in optical engine, and complete testing to determine whether DFI can break the soot/NO_x trade-off with conventional diesel fuel.**
  - Completed.
- **Sept. 30, 2019: Determine sensitivity of DFI to changing four engine operating-condition and/or fuel-injection parameters.**
  - On track.

Approach

Designed to provide stakeholders with high-quality, relevant, unbiased experimental data for making informed decisions regarding DFI technology.

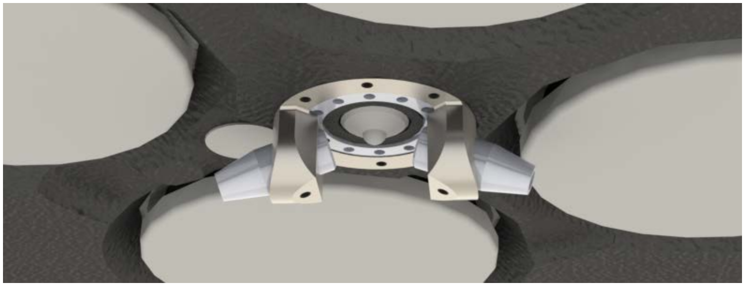
Using the only DFI engine in the world & guidance from industry, conduct sweeps of basic engine operating-condition & fuel-injection parameters to better understand sensitivities.



- **Swept variables**
  - Intake oxygen mole fraction, X_{O2}
  - Duration of injection, DOI
  - Start of combustion, SOC
  - Injection pressure, P_{inj}
  - Intake manifold abs. press., IMAP
  - Intake manifold temperature, IMT
- **Diagnostics**
  - Cylinder pressure
  - Emissions
  - Natural luminosity (NL) imaging

Technical accomplishments

Successfully installed & aligned a two-duct holder to test DFI in the optical engine

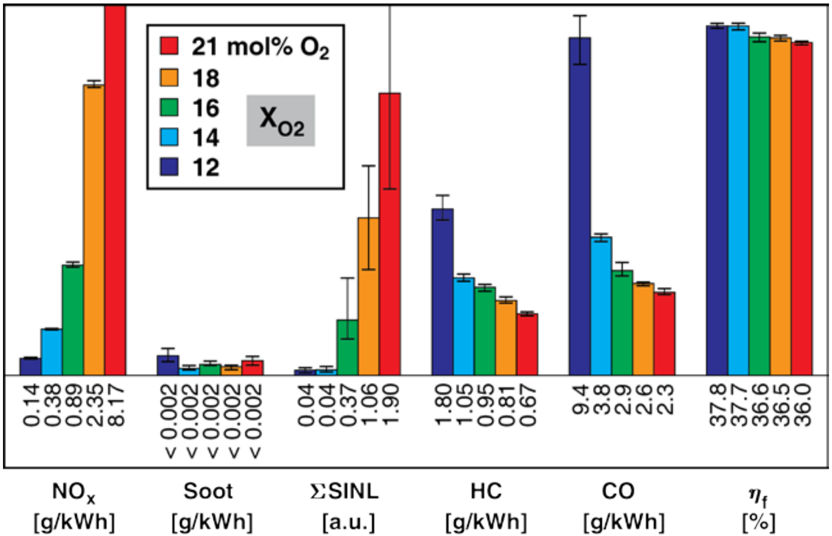


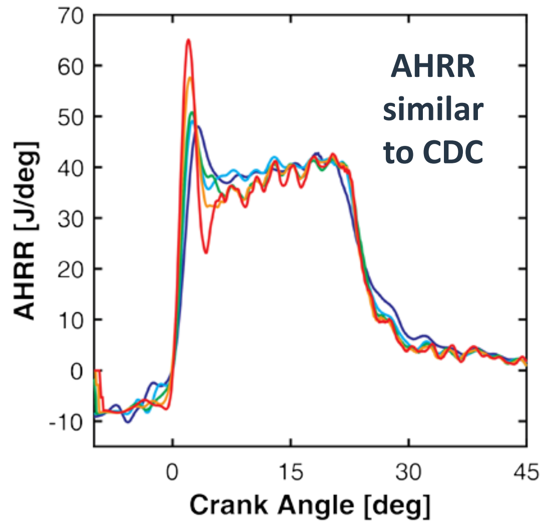
- **Duct configuration**
  - 2 mm inner diam., 12 mm long, inlet 3 mm from inj. orifice exit
- **Injector tip**
  - 2 × 0.108 mm × 140°
  - Load ≈ 2.6 bar gross IMEP
- **Fuel**
  - No. 2 S15 certification diesel
- **1200 rpm engine speed**

Research engine	Single-cyl.
Cycle	4-stroke CI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Displacement per cylinder	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	16.0:1

IMEP = indicated mean effective pressure; S15 = 15 parts per million sulfur max.; CI = compression ignition

Intake oxygen mole fraction (X_{O2}) sweep shows benefits of DFI with dilution.

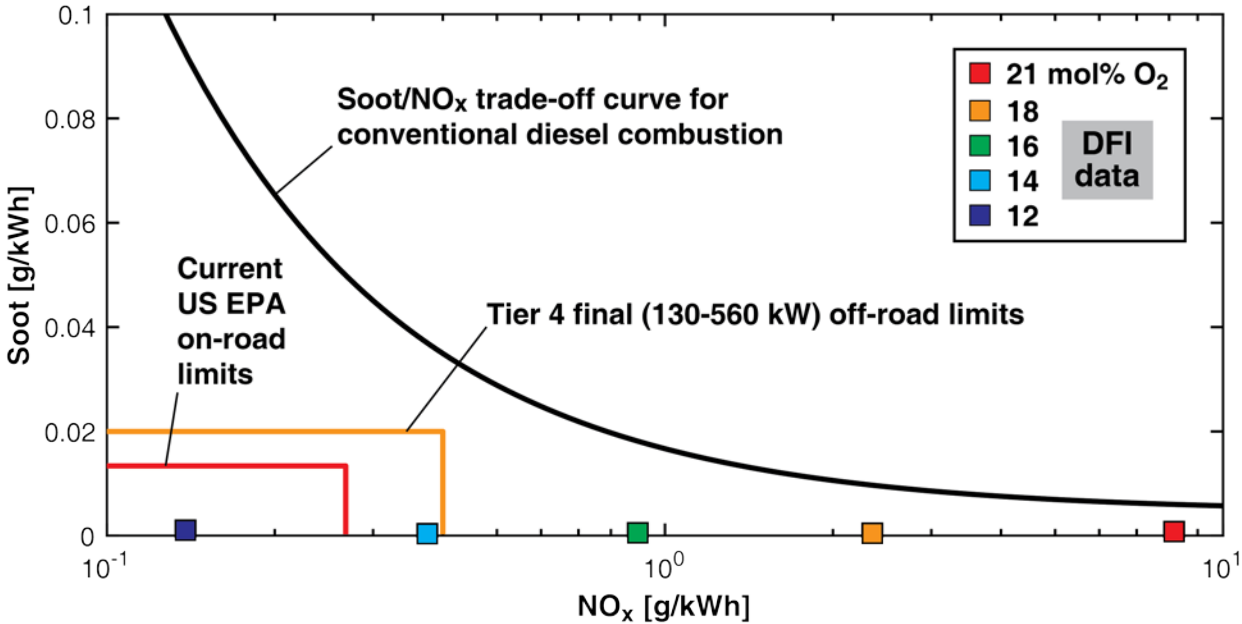




- NO_x is dramatically ↓ without a corresponding soot ↑
- HC & CO emissions ↑ more significantly at highest dilution
- Fuel-conversion efficiency (η_f) improves with dilution

mol% = molar percentage; O_2 = oxygen; ΣSINL = temporally & spatially integrated natural luminosity (indicator of hot, in-cylinder soot); AHRR = apparent heat-release rate; g = grams; kWh = kilowatt-hour; J = Joule; deg = degree

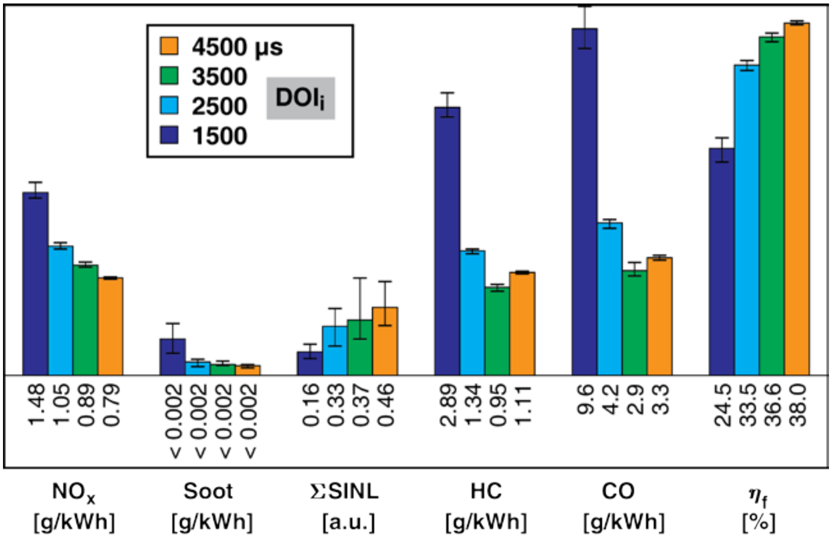
DFI with dilution can break the long-standing diesel soot/NO_x trade-off.

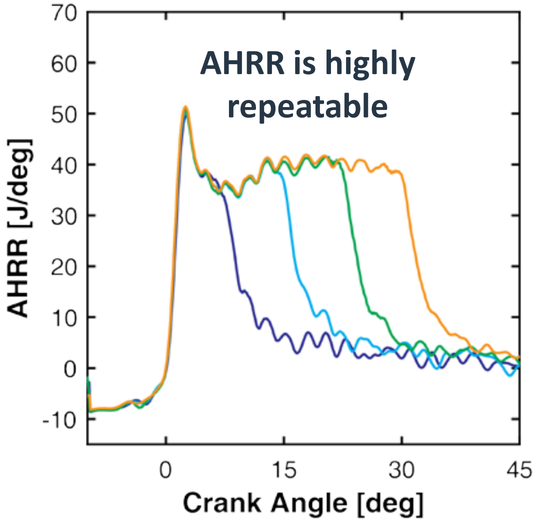


- DFI lowers soot by ~10X to ~100X with current diesel fuel
- Dilution lowers NO_x by ~20X to ~50X

US EPA = United States Environmental Protection Agency; kW = kilowatt

Duration of injection (DOI) sweep shows that longer injections tend to be better.

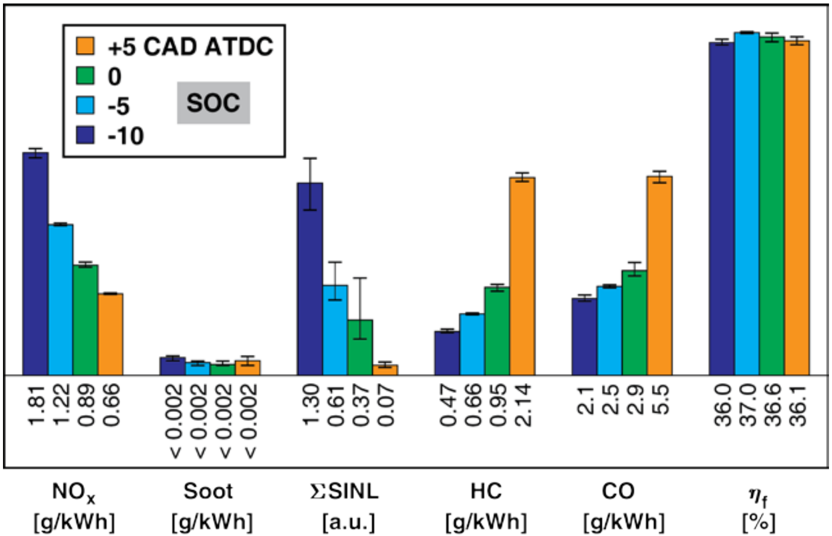


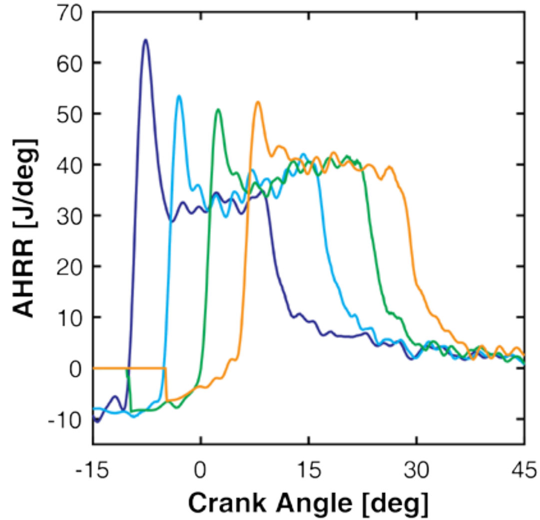


- Longer DOIs tend to produce lower indicated-specific NO_x, HC, & CO emissions, as well as higher η_f

DOI_i = indicated duration of injection (i.e., duration of electronic trigger signal to injector driver)

Start of combustion (SOC) sweep shows that DFI behaves similarly to CDC.

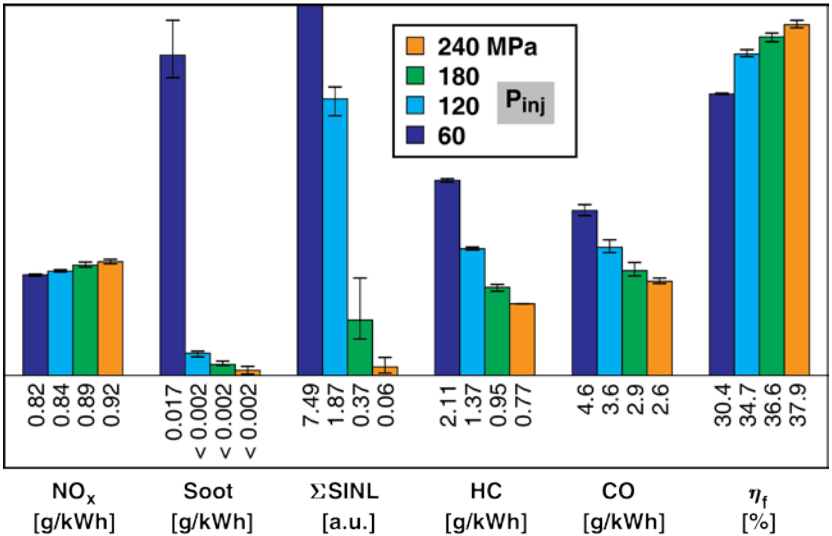


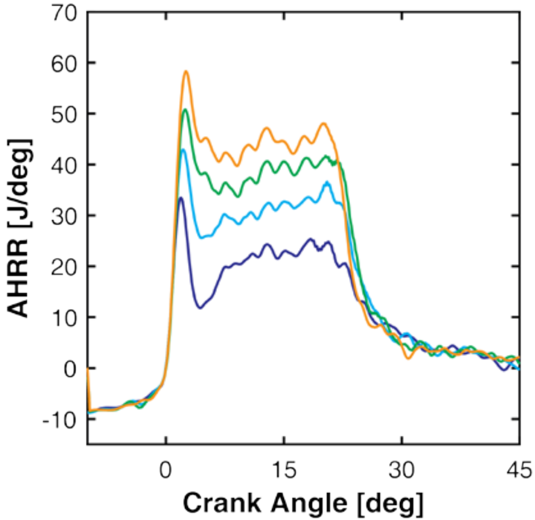


- **Retarding SOC causes NOx ↓, HC & CO ↑**
  - Also facilitates transition to LLFC (indicated by low ΣSINL)
- **η_f does not change significantly for the studied SOC range**

LLFC = leaner lifted-flame combustion (i.e., diesel combustion that does not produce soot); CAD ATDC = crank-angle degrees after top-dead-center

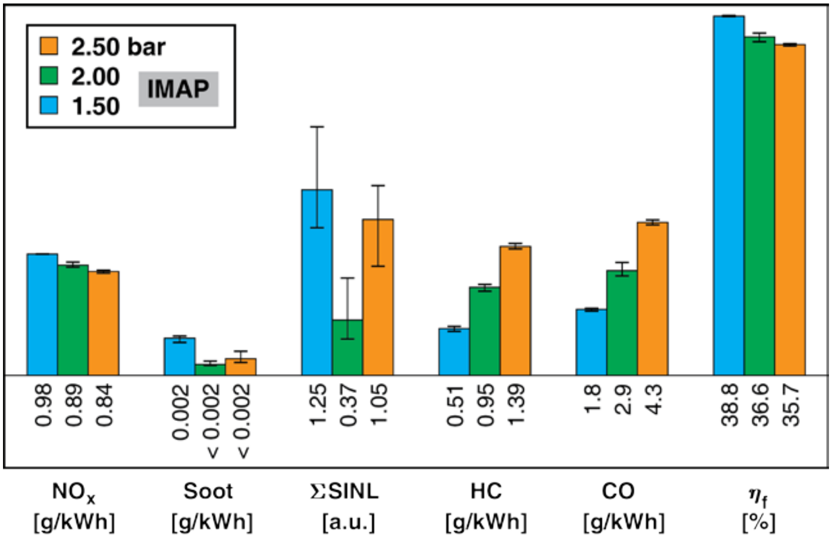
Injection pressure (P_{inj}) sweep shows that higher P_{inj} is largely beneficial.

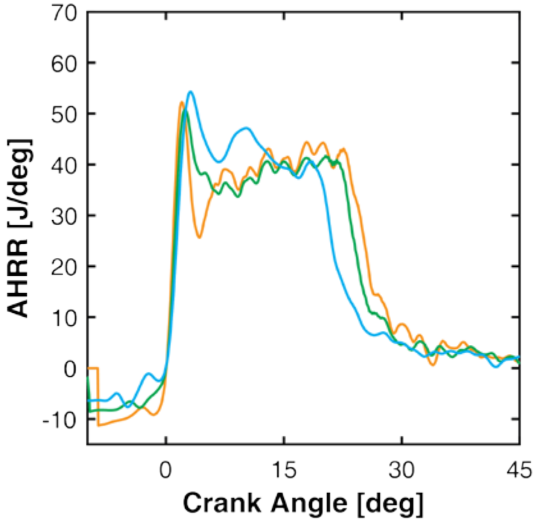




- **Soot, HC, CO, & η_f all improve as P_{inj} ↑**
  - Highest P_{inj} of 240 MPa intermittently achieves LLFC
- **Measureable soot can be produced if P_{inj} is too low**

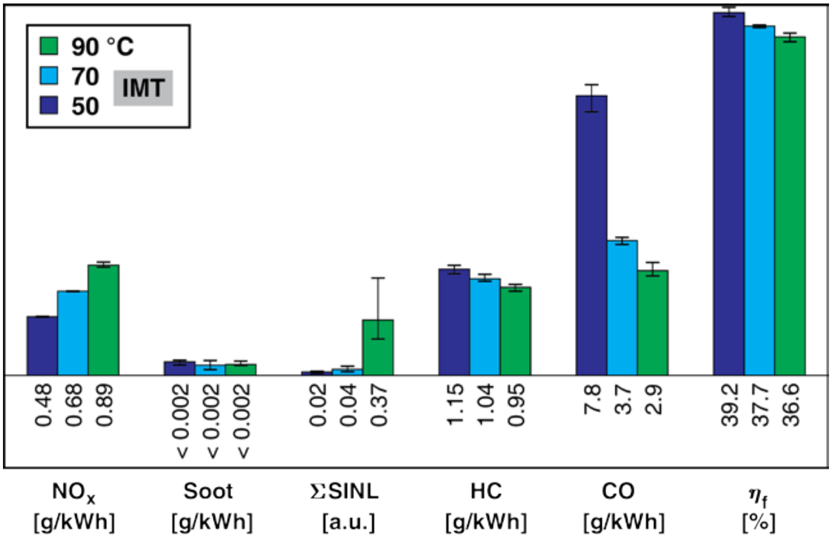
Intake manifold abs. pressure (IMAP) sweep: lower IMAP is generally better.

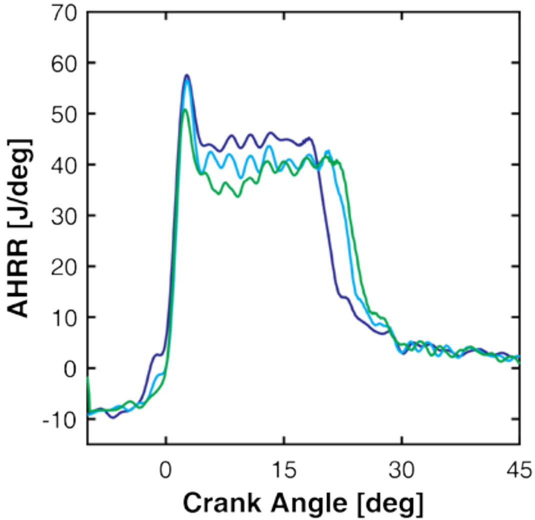




- **HC, CO, & η_f all improve as IMAP ↓**
  - But NO_x & soot degrade slightly
- **Local minimum in ΣSINL at 2.00 bar IMAP baseline condition requires further study**

Intake manifold temperature (IMT) sweep shows mixed results.





- **NO$_x$, ΣSINL, & η_f all improve as IMT↓**
  - Should be beneficial for low NO$_x$ under cold-start operation
  - LLFC intermittently achieved at 50 °C IMT
- **HC & CO↑ somewhat as IMT↓**

Responses to previous year's reviewers' comments

- **No reviewer comments – this project was a new start in FY19.**

Collaboration & coordination with other institutions

- **Co-Optimization of Fuels & Engines Program (Co-Optima)**
  - Two (2) DOE offices, nine (9) national labs, > 20 universities, > 80 stakeholder organizations, > 120 researchers
  - Fuel effects on DFI
- **DOE Technology Commercialization Fund CRADA**
  - Partners: Caterpillar Inc. & Ford Motor Co.
  - Two-year project, started in FY19
  - Overcoming barriers to DFI commercialization
- **Advanced Engine Combustion MOU**
  - 18 companies, 20 universities, seven (7) national labs
  - General guidance & oversight
- **Sibendu Som (Argonne National Lab) & Sotirios Mamalis (Stony Brook University): Large eddy simulations of DFI**

Remaining challenges & barriers

- **What is the potential for DFI to work at high load cond's?**
  - What are the effects of adding more ducts &/or using larger injector-orifice diameters?
- **How sensitive is engine-DFI performance to varying duct geometric parameters?**
  - E.g., duct inside diameter, duct length, & stand-off distance from injector-orifice exit-plane to duct inlet-plane
- **What are the fundamental physical processes governing DFI performance?**
  - How can they be used to determine optimal duct designs?
- **How can the slight drop in thermal efficiency be reversed?**
- **What is required to ensure duct alignment & durability?**

Proposed future research (rest of FY19 & FY20)

Any proposed future work is subject to change based on funding levels.

- **Explore strategies for achieving high load DFI operation**
  - Adding more ducts (six if possible, otherwise four)
  - Using larger injector-orifice diameters (~∅.175 mm)
- **Quantify sensitivity of engine-DFI performance to varying duct geometric parameters**
  - Duct inside diameter (∅2 mm vs. ∅3 mm)
  - Length (8 mm vs. 12 mm vs. 16 mm)
- **Develop an improved understanding of the fundamental physical processes governing DFI performance**
  - Use existing literature, theoretical analysis, & computational investigations

Summary

Relevance	This research directly supports the DOE Vehicle Technologies Office mission of providing "low cost, secure, and clean energy technologies to move people and goods across America" & a key industry objective of simultaneously lowering diesel NO_x & soot.
Approach	• Conducted the world's first DFI experiments in an engine. • All milestones are either completed or on track.
Technical accomplishments	• Tested DFI while sweeping X_{O2}, DOI, SOC, P_{inj}, IMAP, & IMT. • DFI with dilution can break the long-standing diesel soot/NO_x trade-off, potentially enabling a new generation of clean, cost-effective engines that are compatible with current fuels. • In many respects, DFI performs similarly to CDC, except with substantially lower soot emissions.
Collaboration & coordination	The work is closely integrated with Co-Optima, the Advanced Engine Combustion MOU, & industry through a CRADA.
Future research	Addresses key technical barriers to DFI implementation: increasing load, understanding duct-geometry sensitivities, & optimizing performance for different applications.