An Optical-Engine Investigation of Conventional Diesel Combustion, Cooled Spray, and Ducted Fuel Injection Technologies for Heavy-Duty Engines

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Research supported by: ***U.S. Dept. of Energy, Vehicle Technologies Office***
Program managers: ***Kevin Stork, Siddiq Khan, Gurpreet Singh,*** *&* ***David Ollett***

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
Sandia National Laboratories

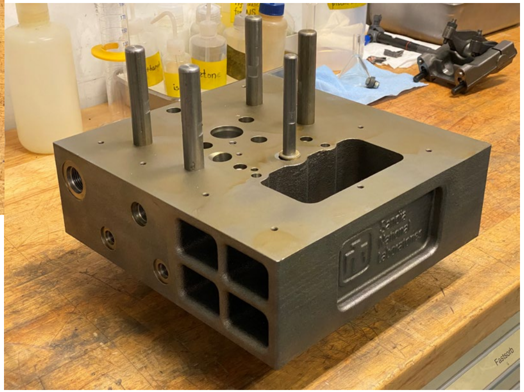
ASME ICE Forward Conference
San Antonio, TX
October 21, 2024

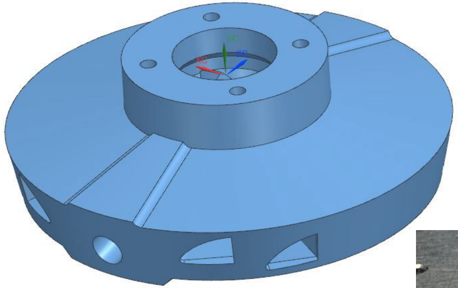
Objective

- **Evaluate Conventional Diesel Combustion (CDC), Cooled Spray (CS), & Ducted Fuel Injection (DFI) technologies for locomotive applications**
  - Emissions & efficiency performance for each strategy
  - Effects of scaling duct diameter for larger injector orifice diameter
  - Elucidate underlying reasons for observations

New engine components

- **New optical piston**
  - Titanium alloy
  - Req'd for 20 MPa peak cylinder pressure (PCP)
- **New cylinder head**
  - Also for 20 MPa PCP
- **CS inserts**
- **Duct modules**
- **Fuel injectors**



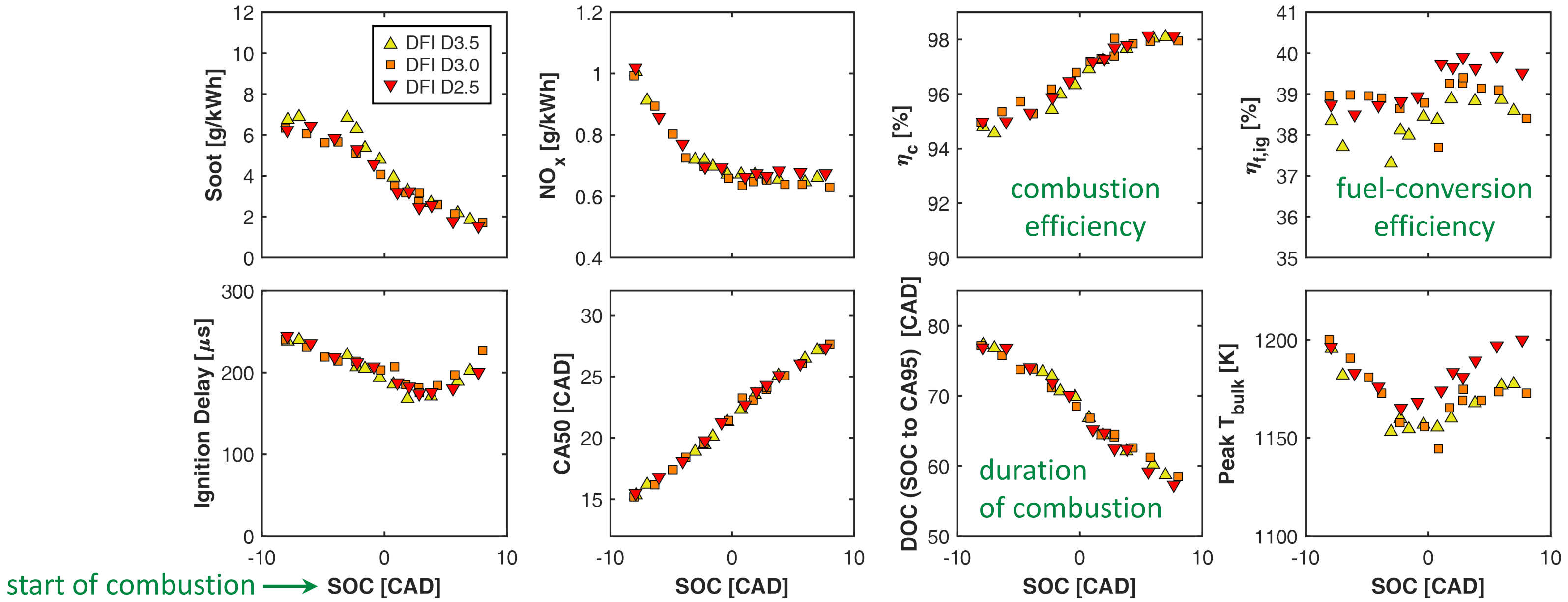


Optical-engine parameters

- **Mode 4 of EPA SET**
  - 75%-load, mid-speed condition
- **2-hole nozzle with large orifices**
  - To simulate larger (locomotive) engine
- **Matching**
  - Orifice diameter, engine speed, P_{inj}, XO_2, TDC P & T

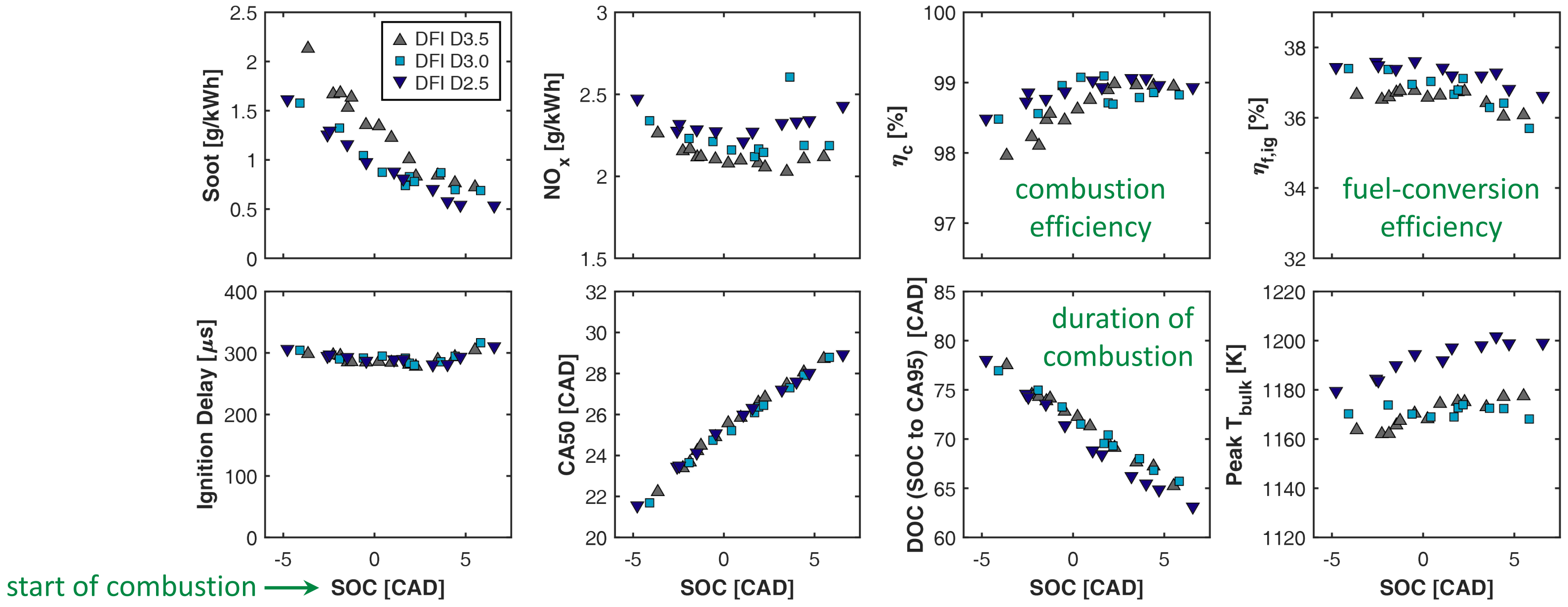
Parameter	EGR Condition	Non-EGR Condition
Injector-tip configuration	2 × .290 mm × 155°	
Injected fuel quantity	144.2 mg/stroke	152.2 mg/stroke
Injection pressure (P_{inj})	220 MPa	150 MPa
Injector-tip protrusion	4.5 mm	
Engine bore × stroke	∅125 mm × 140 mm	
Engine speed	1500 RPM	
CS configurations tested	2D[2.5,3.0]L12G2.5	
DFI configurations tested	2D[2.5,3.0,3.5]L12G3δ	
Piston-bowl configuration	∅103 mm × 9 mm deep	
Intake-O_2 mole fraction (XO_2)	17.0 mol%	20.95 mol%
Start of combustion (SOC)	Swept	
Intake manifold abs. press. (IMAP)	4.00 bar	3.50 bar
Motored cylinder pressure at TDC	133 bar	123 bar
Intake manifold temperature (IMT)	83 °C	71 °C
Motored bulk in-cyl. temperature at TDC	890 K	860 K
Fuel	Off-road No. 2 diesel	

DFI duct-diameter study: EGR



- **DFI D2.5 performs ~same or better than D3.0 for all plotted parameters**
  - Particularly fuel-conversion efficiency ($\eta_{f,ig} \equiv$ work output / chem. energy input)
  - Performance improves for retarded timings

DFI duct-diameter study: Non-EGR



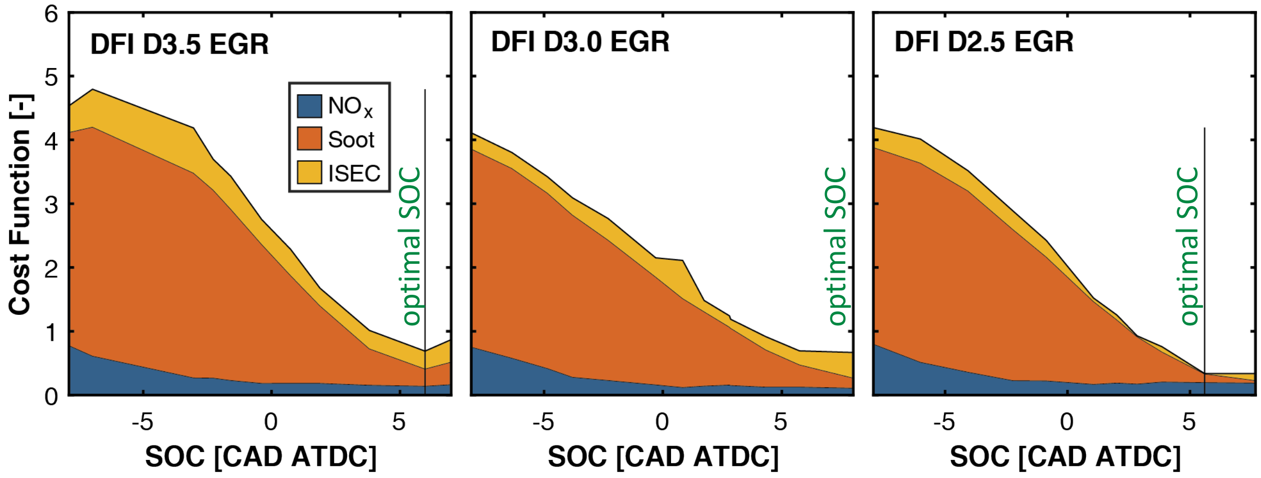
- **Similar trends as EGR condition: DFI D2.5 seems to have best performance**
  - NO_x is slightly higher for D2.5, maybe due to higher T_{bulk}
- **Need a way to quantify & evaluate performance for different SOC, strategy, ...**

Cost function

$$C_i \equiv \frac{ISSoot_i - min(ISSoot)}{min(ISSoot)} + \frac{ISNO_{x,i} - min(ISNO_x)}{min(ISNO_x)} + \frac{ISEC_i - min(ISEC)}{max(ISEC) - min(ISEC)}$$

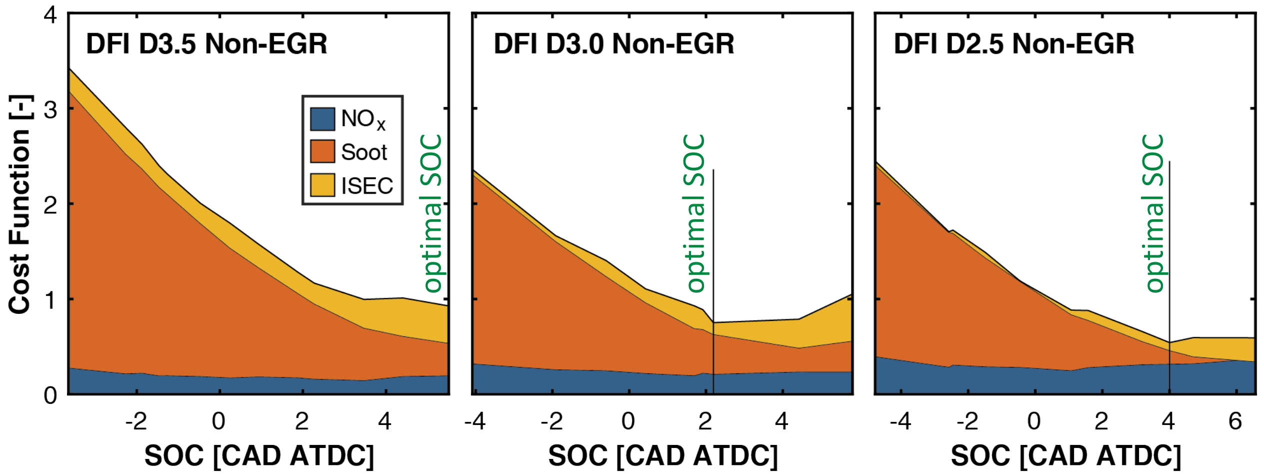
- $\boldsymbol{i}$ = **index unique to given combustion strategy & operating condition**
- $\boldsymbol{ISSoot}$ & $\boldsymbol{ISNO_x}$ = **indicated–specific soot & NOx, respectively**
- $\boldsymbol{ISEC}$ = **indicated-specific energy consumption =** $\boldsymbol{\eta_{f,ig}^{-1}}$
- **Min. & max. values for each parameter are taken from all combustion strategies & all operating conditions *at the same EGR level***
- $\boldsymbol{C_i}$ **is always ≥ 0**
- **Best performance is achieved when** $\boldsymbol{C_i}$ **is minimized**
- $\boldsymbol{C_i}$ **is sensitive to small changes in** $\boldsymbol{ISEC}$ **(different normalization)**

Cost-function evaluation of DFI config's: EGR



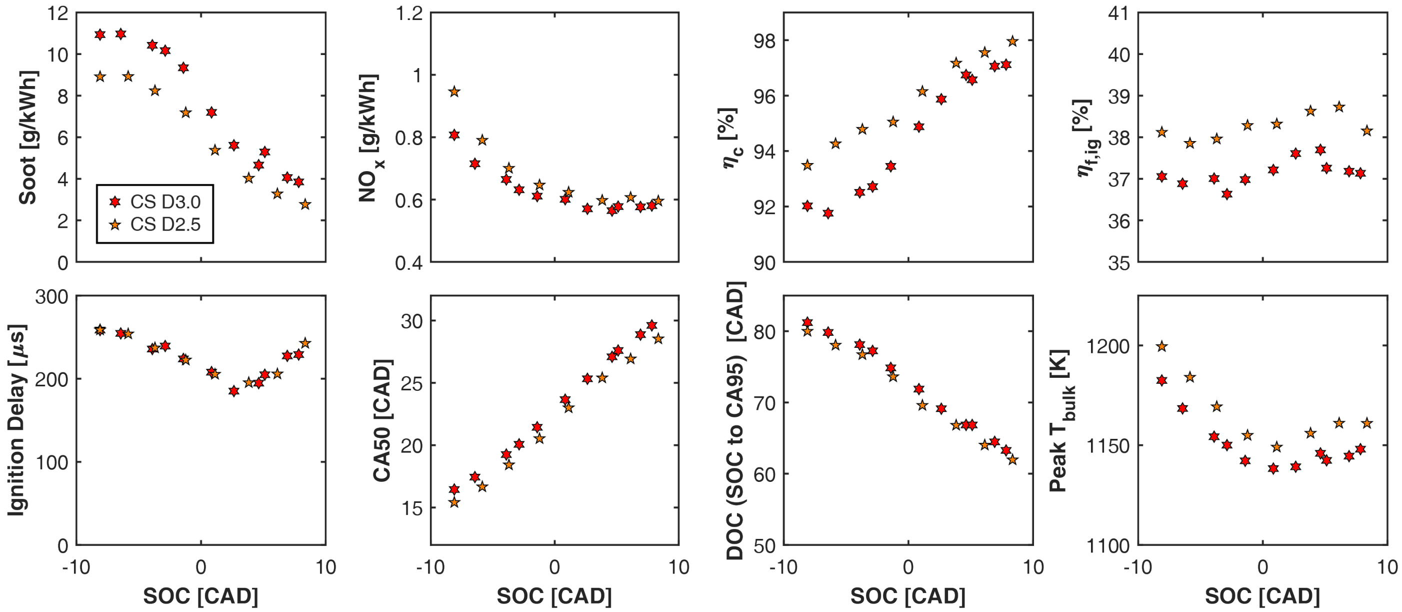
- **Minimum cost-function values decrease consistently with duct diameter**
  - D3.5, Min. C = 0.690 at SOC = 5.97 CAD ATDC
  - D3.0, Min. C = 0.669 at SOC = 8.01 CAD ATDC
  - D2.5, Min. C = 0.338 at SOC = 5.59 CAD ATDC

Cost-function evaluation of DFI config's: Non-EGR



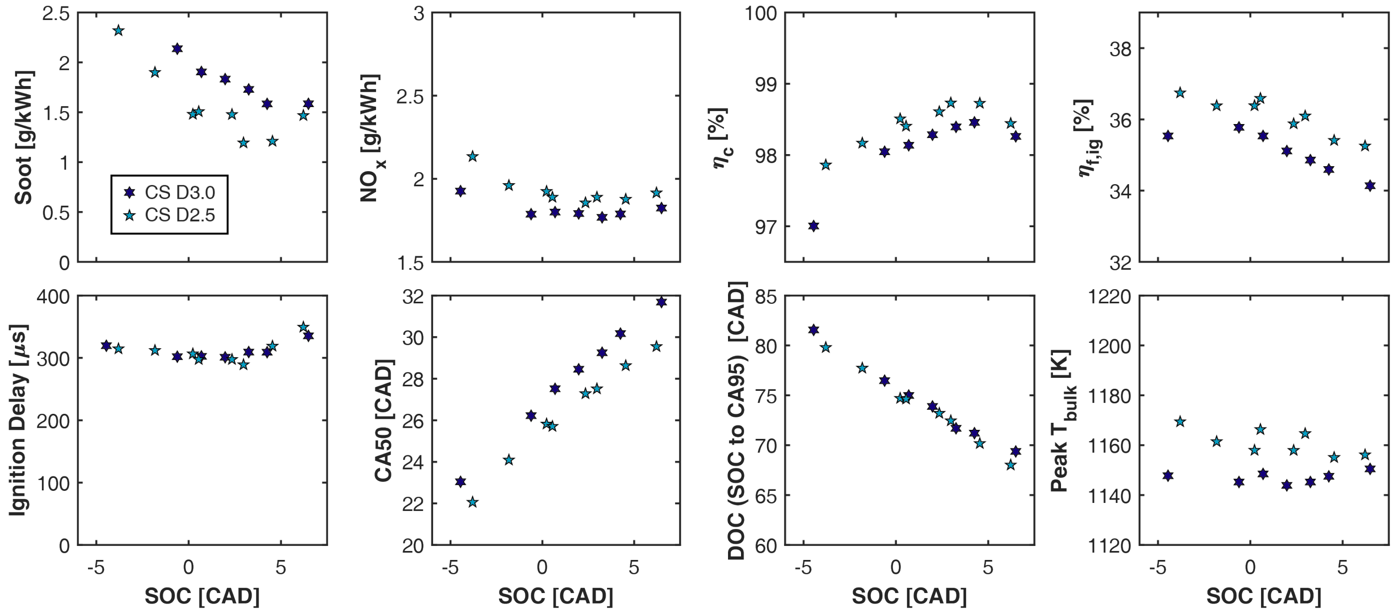
- **Minimum cost-function values decrease consistently with duct diameter**
  - D3.5, Min. C = 0.927 at SOC = 5.51 CAD ATDC
  - D3.0, Min. C = 0.752 at SOC = 2.19 CAD ATDC
  - D2.5, Min. C = 0.542 at SOC = 4.00 CAD ATDC
- **Conclusion: DFI D2.5 configuration is most promising**

CS duct-diameter study: EGR



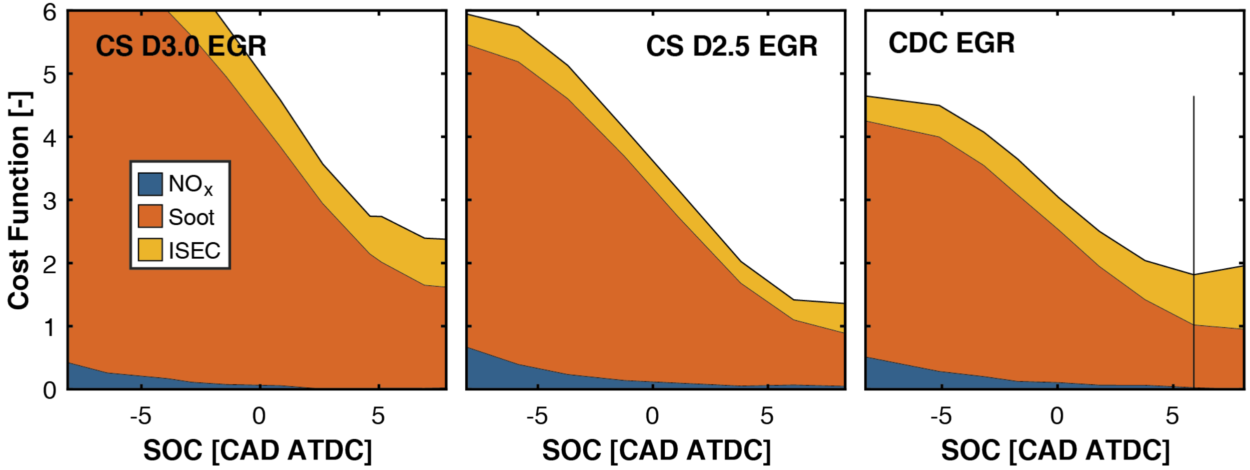
- **CS D2.5 performs ~same or better than D3.0 for all parameters except NO_x**
  - NO_x increases are small, especially at retarded timings

CS duct-diameter study: Non-EGR



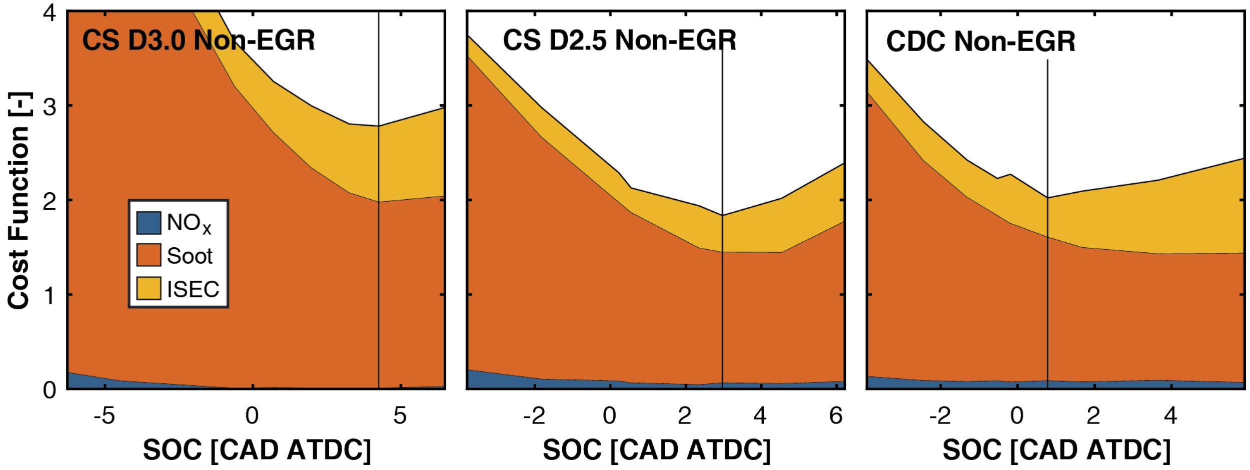
- **Similar trends as EGR condition: CS D2.5 seems to have best performance**
  - NO_x is again slightly higher for D2.5, maybe due to higher T_{bulk}

Cost-function evaluation of CS & CDC config's: EGR



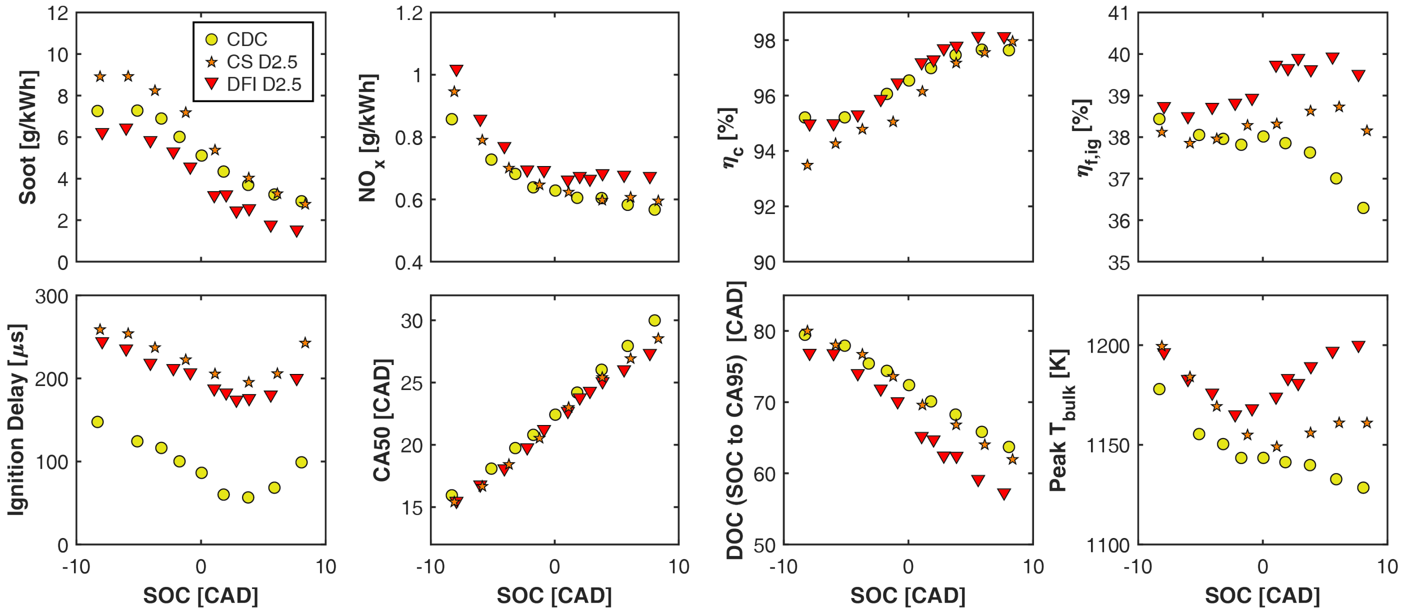
- **Minimum cost-function value decreases with duct diameter**
  - CS D3.0, Min. C = 2.377 at SOC = 7.83 CAD ATDC
  - CS D2.5, Min. C = 1.359 at SOC = 8.35 CAD ATDC
  - CDC, Min. C = 1.815 at SOC = 5.89 CAD ATDC
- **CS D2.5 performs better than CDC**

Cost-function evaluation of CS & CDC config's: Non-EGR



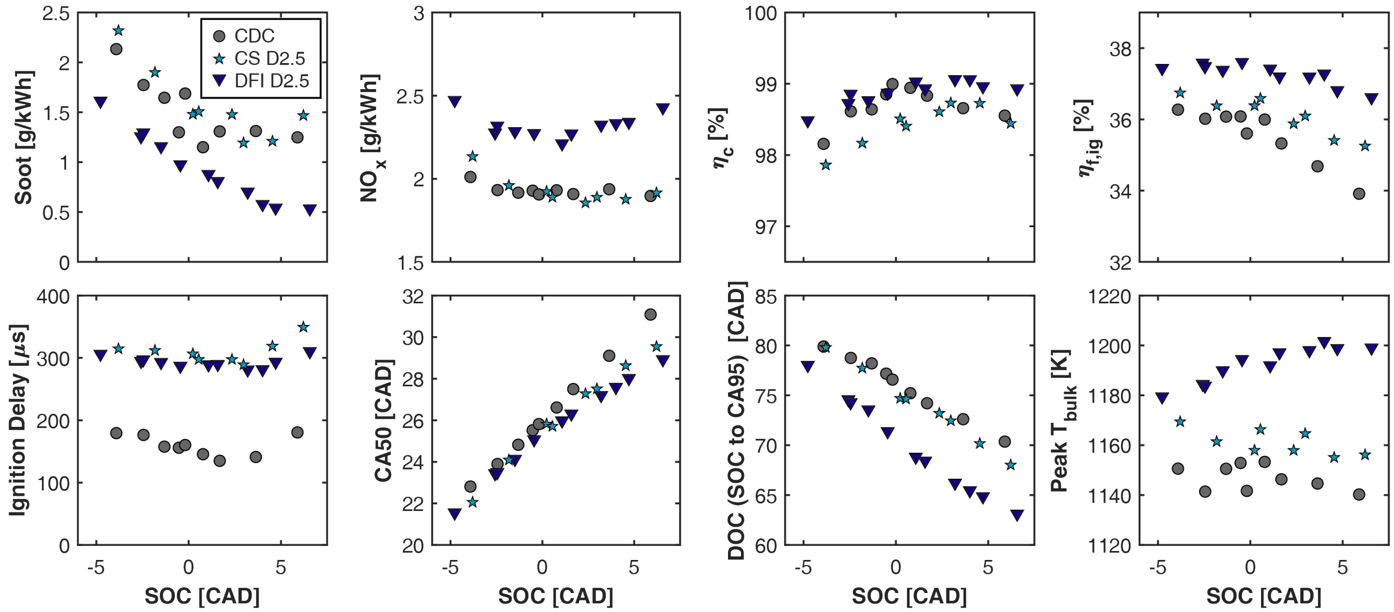
- **Minimum cost-function value decreases with duct diameter**
  - CS D3.0, Min. C = 2.782 at SOC = 4.25 CAD ATDC
  - CS D2.5, Min. C = 1.836 at SOC = 2.97 CAD ATDC
  - CDC, Min. C = 2.022 at SOC = 0.78 CAD ATDC
- **Conclusion: CS D2.5 config. is most promising & performs better than CDC**

Evaluation of CDC, CS D2.5, & DFI D2.5: EGR



- **DFI performs ~same or better than CDC & CS for all parameters except NO_x**
  - NO_x differences are generally small

Evaluation of CDC, CS D2.5, & DFI D2.5: Non-EGR



- **Similar trends as EGR condition: DFI D2.5 seems to have best performance**
  - NO_x is again higher for DFI D2.5, maybe due to higher T_{bulk}

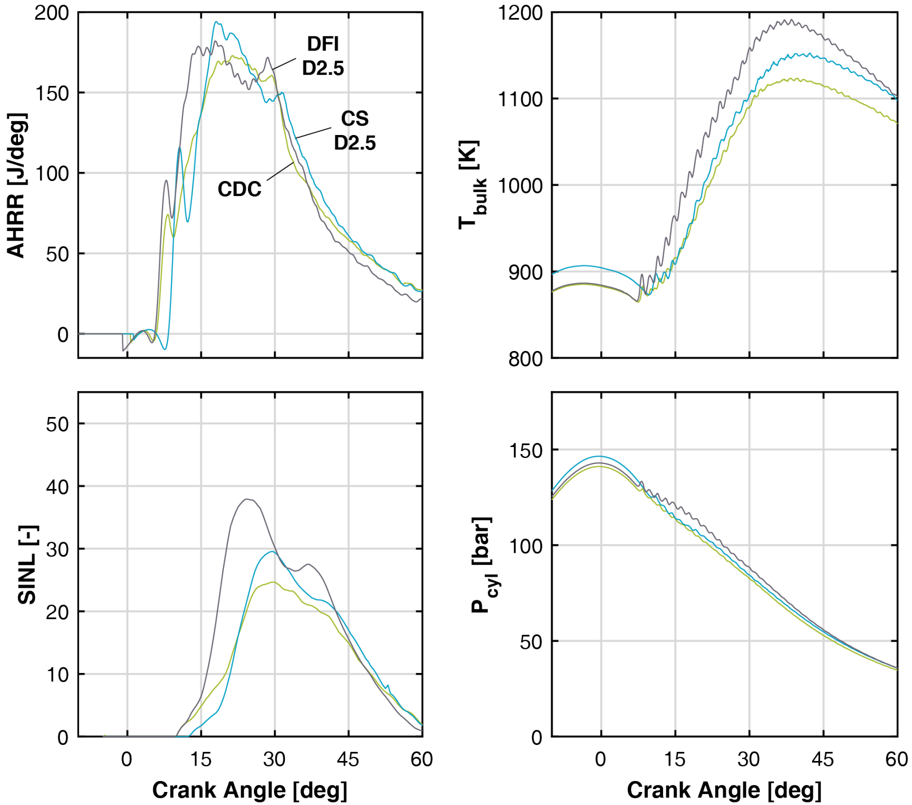
Cost-function summary for all tested conditions

- **CS performs better than CDC**
  - EGR: 25% lower cost function
  - Non-EGR: 9% lower
- **DFI performs better than CDC & CS**
  - EGR
    - 81% lower than CDC
    - 75% lower than CS
  - Non-EGR
    - 73% lower than CDC
    - 71% lower than CS
- **Why?**

Operating Condition		Optimal Cost-Function Value [-]	Optimal SOC [CAD]
EGR	CDC	1.82	5.9
	CS	1.36	8.4
	DFI	0.34	5.6
Non-EGR	CDC	2.02	0.8
	CS	1.84	3.0
	DFI	0.54	4.0

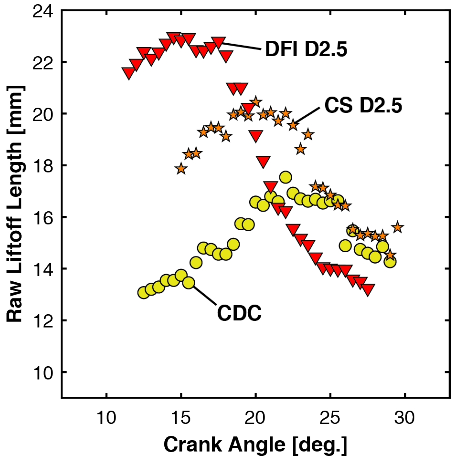
Compare strategies @ optimal SOCs: EGR

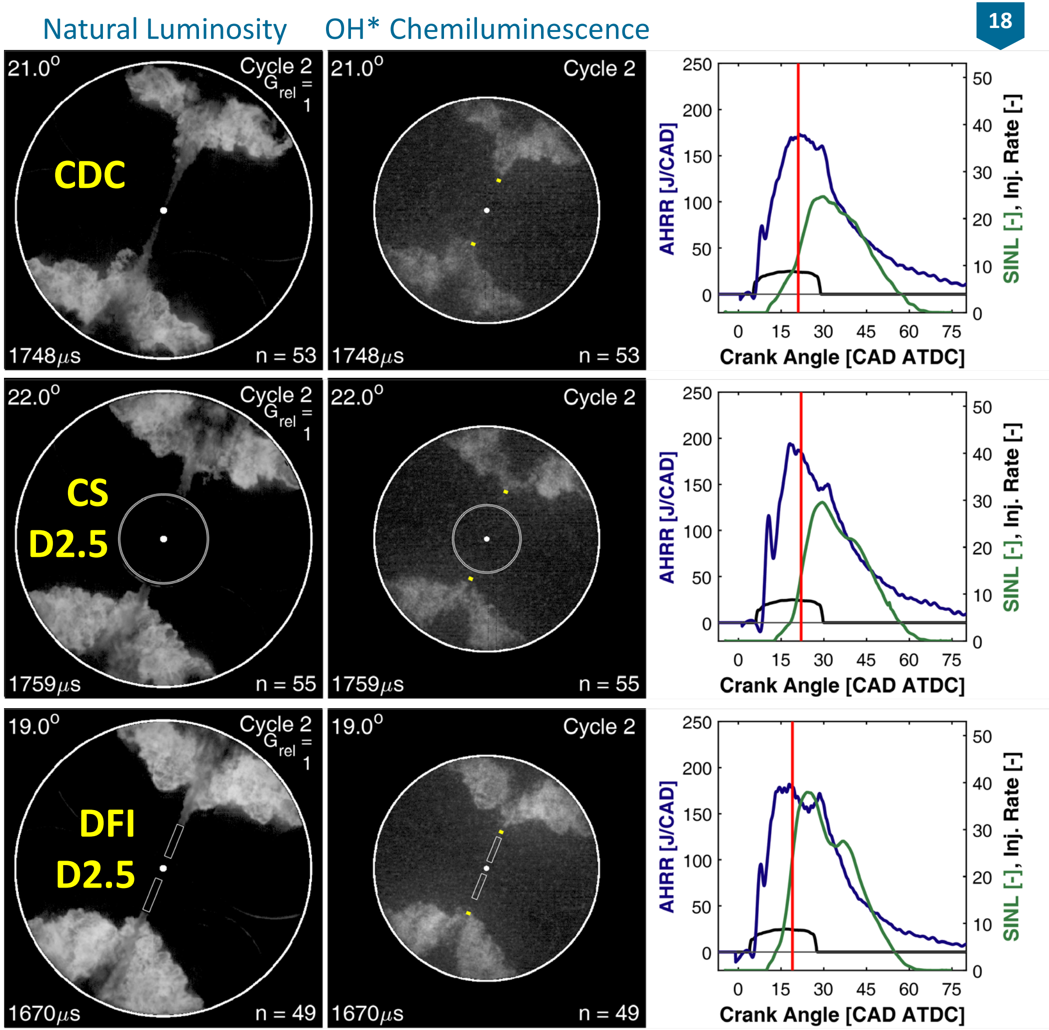
- **Timing corresponds to min. cost function for each strategy w/ EGR**
- **AHRR is generally advanced for DFI**
  - Despite same SOC as CDC
- **Leads to higher T_{bulk} values**
  - Due to more-premixed combustion?
  - Enhancing late-cycle soot oxidation?
- **AHRR drops faster during late-cycle burn-out for DFI**
- **Higher SINL implies hotter soot**



Movies @ optimal SOC: EGR

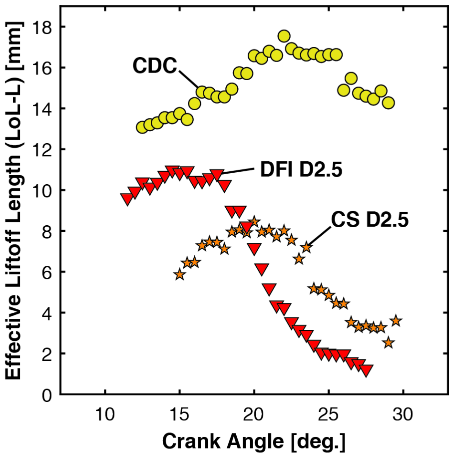
- CS may be entraining combustion products before EOI
- Raw liftoff lengths (LoLs) are longer for DFI & CS…

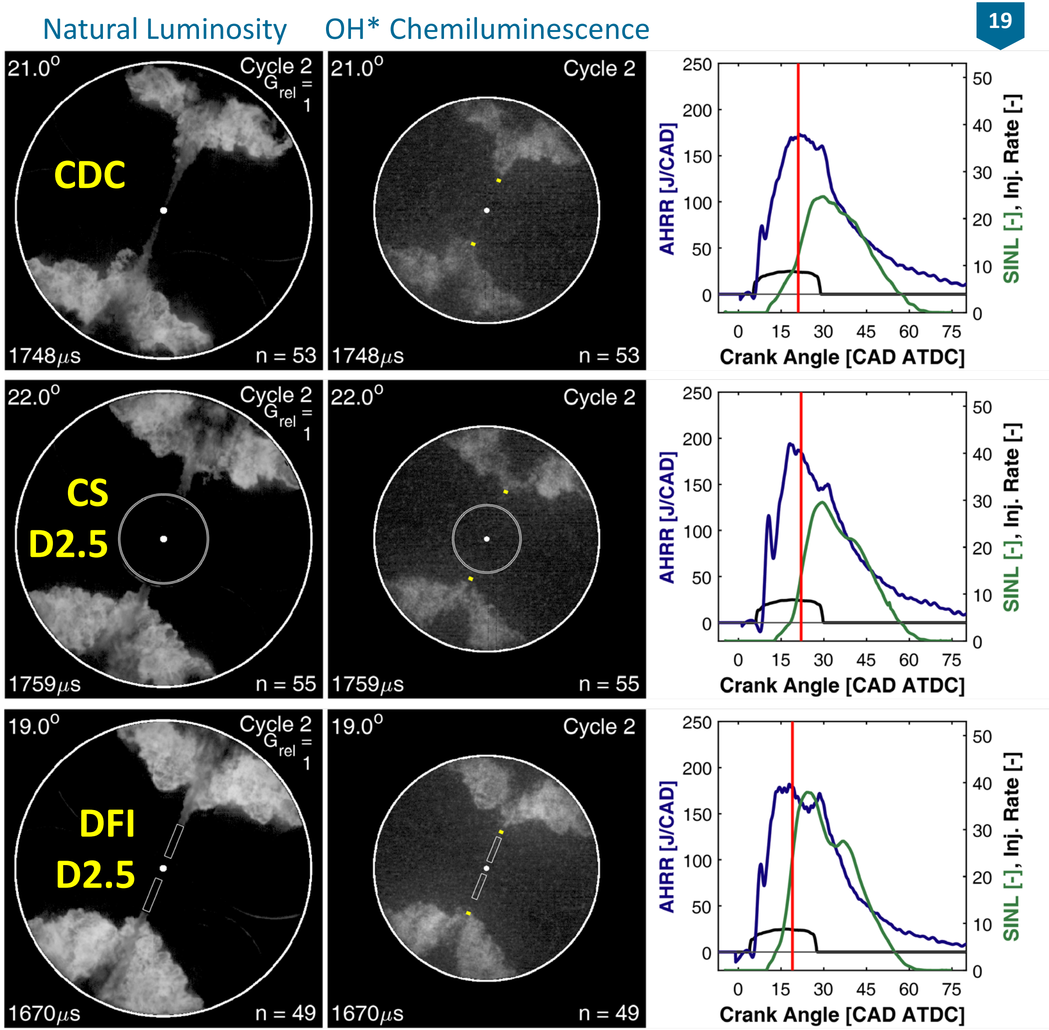




Movies @ optimal SOC: EGR

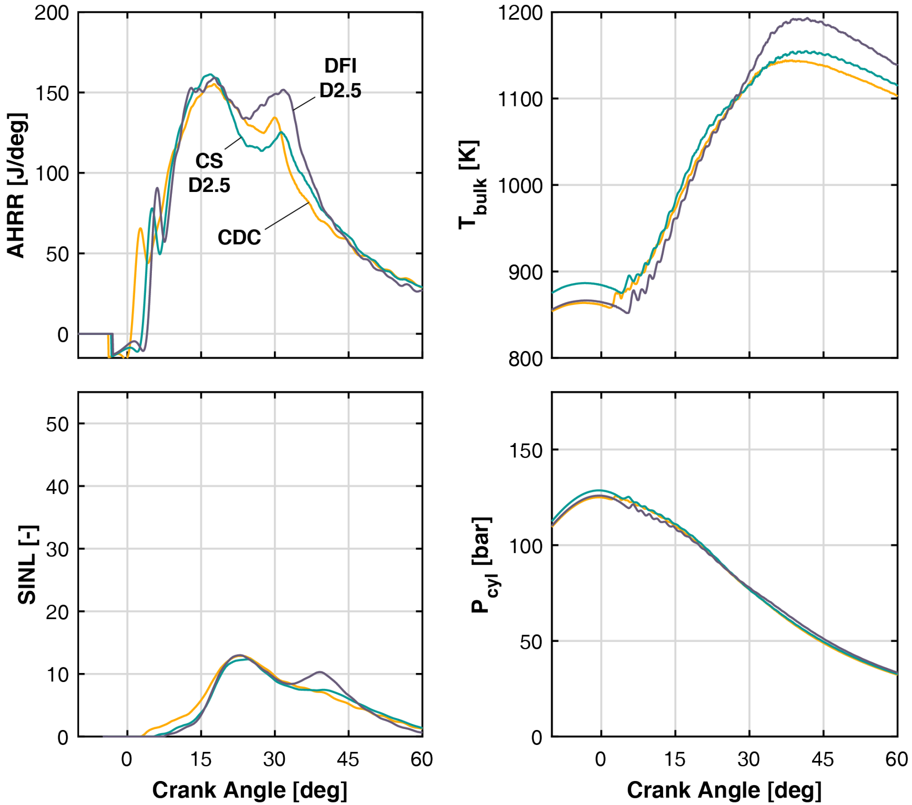
- CS may be entraining combustion products before EOI
- Raw liftoff lengths (LoLs) are longer for DFI & CS…
- …but effective LoLs are shorter





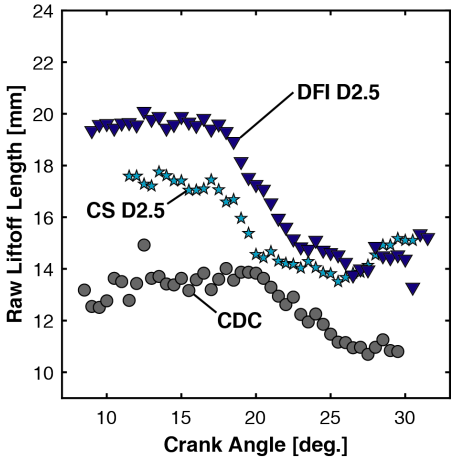
Compare strategies @ optimal SOCs: Non-EGR

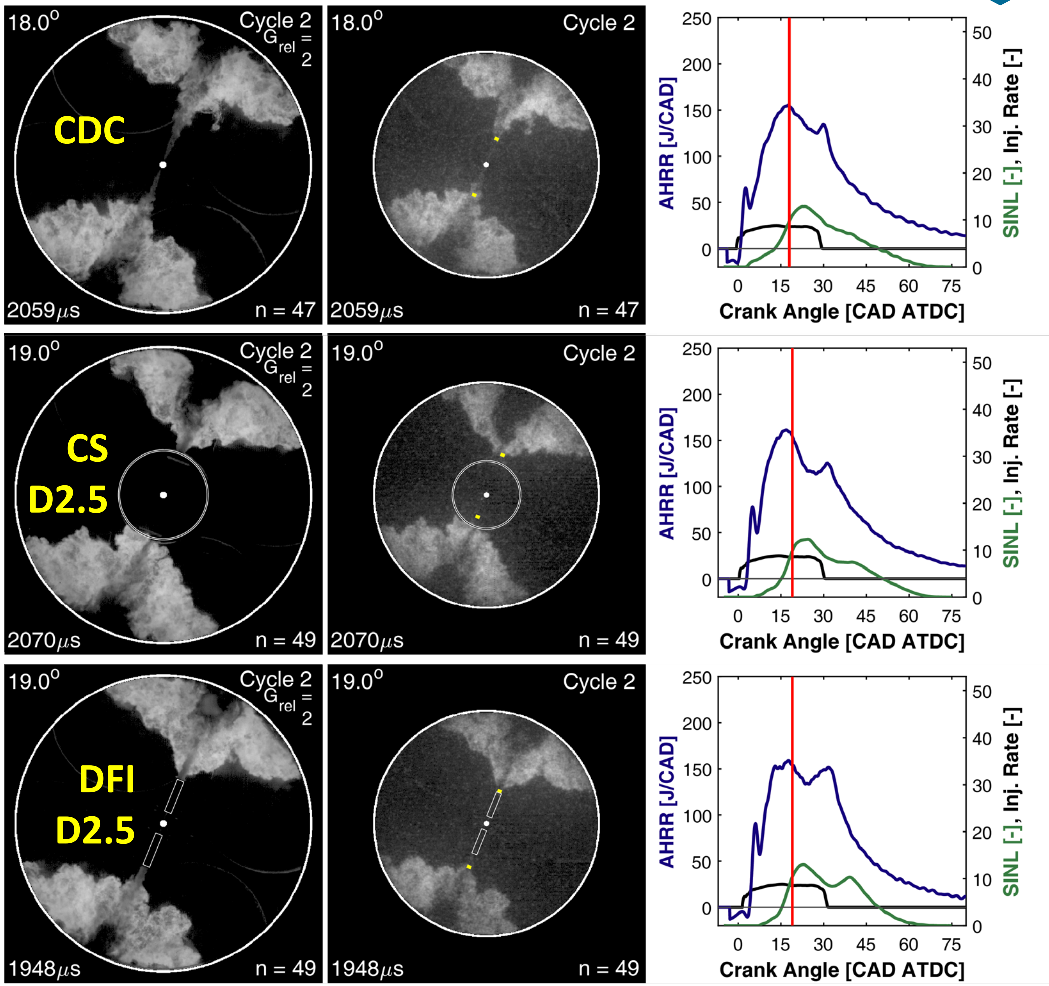
- **Timing corresponds to min. cost function for each strategy w/o EGR**
- **AHRR is generally advanced & larger for DFI**
  - Particularly near EOI
- **Leads to higher T_{bulk} values**
- **AHRR drops more quickly during late-cycle burn-out for DFI**



Movies @ optimal SOC: Non-EGR

- **Again see evidence of CS ingesting combustion products before EOI**
  - This is not observed for DFI
  - Preventing this could improve CS performance





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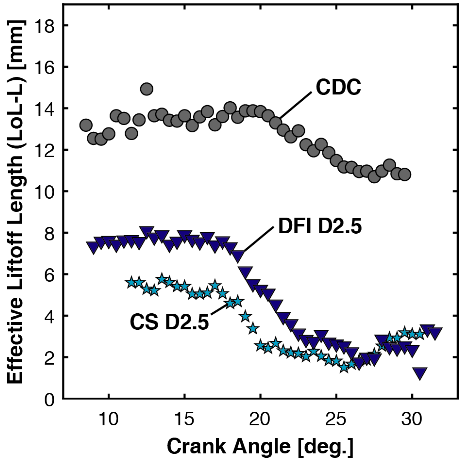

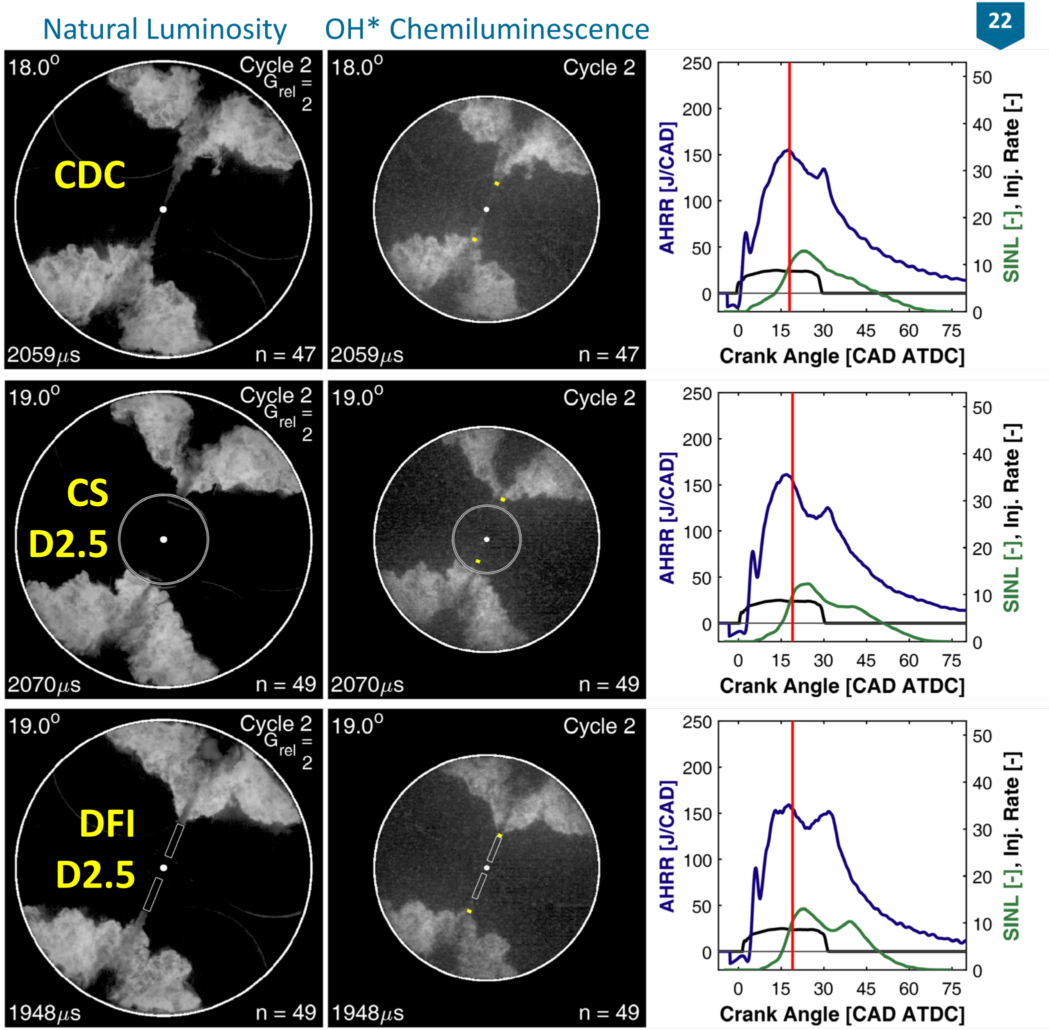

Summary

- **Optimal duct diameter = 2.5 mm for CS & DFI**
  - Didn't change despite orifice diam. changing from .110 mm to .288 mm (6.9X flow area ↑)
- **Both CS & DFI generally outperform CDC**
  - DFI has lowest cost fcns. for the tested cond's
- **Processes of potential importance for future optimization (all may be related)**
  - Extent of flame liftoff from duct/passage exit
  - Entrainment of combust'n products into duct
  - Ignition within duct
  - Spray/bowl interaction

Operating Condition		Optimal Cost-Function Value [-]	Optimal SOC [CAD]
EGR	CDC	1.82	5.9
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