U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – GROUND VEHICLE SYSTEMS CENTER

Innovation Talk: FY18 Innovation Project “Combustion Strategies for Low Ignition Quality Fuels”

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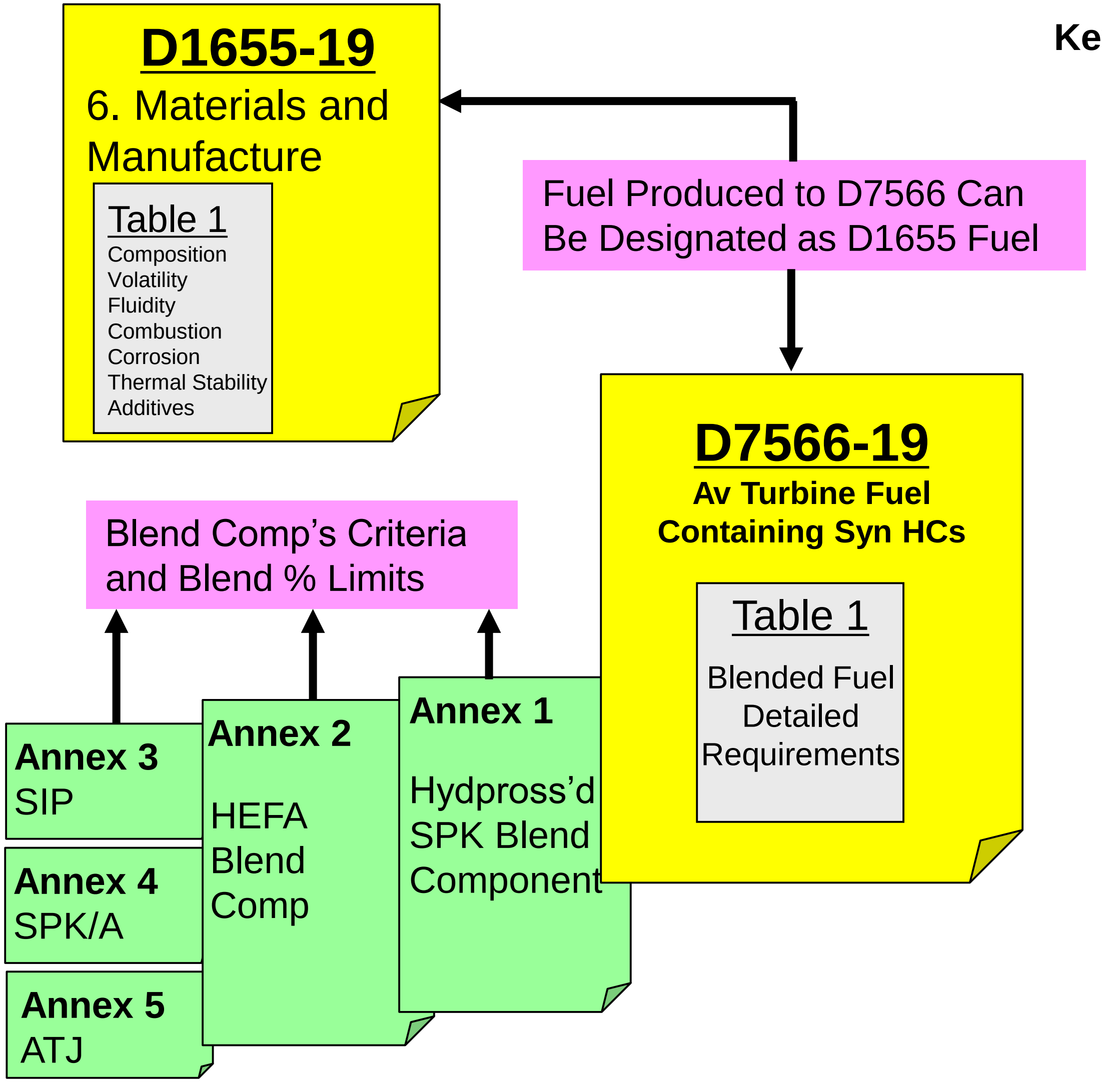
ACKNOWLEDGMENTS

- **Co-Investigators: Eric Gingrich and Steve Stoll (GVPM)**
- **FY18 Innovation Project funding: Office of the Chief Scientist**
- **Low-cetane fuel source: Tim Edwards (AFRL)**
- **Fuel property testing: Nichole Hubble (GSPF) and Scott Hutzler (SwRI)**

INTRODUCTION

- **The DOD is the largest consumer of energy in the U.S.**
- **Semi-synthetic jet fuels are qualified for operational use in DOD ground vehicles on a limited basis**
  - U.S. civil aviation turbine fuel specifications: ASTM D1655 and ASTM D7566
    - Jet A, Jet A-1: no cetane number requirement, maximum synthetic fuel volume fraction
    - F-24: Jet A with military additives (SDA, CI/LI, FSII, optionally AO & MDA)
  - DOD aviation turbine fuel specification: MIL-DTL-83133 (version K, 20180718)
    - JP-8 (F-34), F-35, JP-8+100 (F-37)
    - Minimum derived cetane number (DCN), maximum synthetic fuel volume fraction
- **Petroleum fuel is a mixture of hundreds of different hydrocarbon (HC) compounds, whereas the variety of HC types in a synthesized fuel is much smaller**
  - Synthetic fuels may therefore resemble a single-component fuel
  - Highly branched alkanes exhibit low reactivity (low cetane rating/high octane rating), which affects the combustion process in compression-ignition engines
    - Sasol iso-paraffinic kerosene (IPK): cetane ~ 30
    - Gevo alcohol-to-jet (ATJ): cetane ~ 15
- **New fuel catalysis technologies continue to be developed**
  - DOE anticipates that five new jet and green diesel fuel plants will become operational in the U.S. for bulk fuel production by 2020

ASTM D7566 FUEL SPECIFICATION



D1655-19

6. Materials and Manufacture

Table 1

Composition
Volatility
Fluidity
Combustion
Corrosion
Thermal Stability
Additives

Fuel Produced to D7566 Can Be Designated as D1655 Fuel

D7566-19

Av Turbine Fuel Containing Syn HCs

Table 1

Blended Fuel Detailed Requirements

Blend Comp's Criteria and Blend % Limits

Annex 1

Hydpross'd SPK Blend Component

Annex 2

HEFA Blend Comp

Annex 3

SIP

Annex 4

SPK/A

Annex 5

ATJ

Key Provisions

- Body of Spec Applies to Finished Semi-Synthetic Fuel
- Annex for Each Class of Synthetic Blending Component
- Allow Re-Certification to D1655

  No need for separate tracking
- Synthetic blending components *not approved* for use in aviation engines unless blended with conventional components
- Annexes 1 – 5
  - FT-SPK*
  - HEFA*
  - SIP**
  - FT-SPK/A
  - ATJ-SPK***

*DOD approved air and ground
**Navy approved air only
***Army approved air only

MOTIVATION

- **Demonstrate a potential technical solution that allows the use of low-cetane jet fuels (DCN < 40) in DOD ground vehicles if the operational scenario required it**
  - Challenge: low-cetane fuels may exhibit excessive ignition delay at engine operating conditions with low in-cylinder temperature and density[1]
  - Deliverable: proof of concept that an advanced direct-injection fueling strategy can expand the operational suitability of low-cetane jet fuels in military diesel engines

* DoDI 4140.25 (effective 20150625, with Change 1 dated 20171006) cancelled the fuel standardization policy (i.e. single fuel concept) of DoDD 4140.25 (20040412)

- Mandates the use of commercial and host-nation sources of fuel, including qualified alternative fuels
- “achieve the greatest practical flexibility, sustainment of forces, and minimization of DoD expenses”

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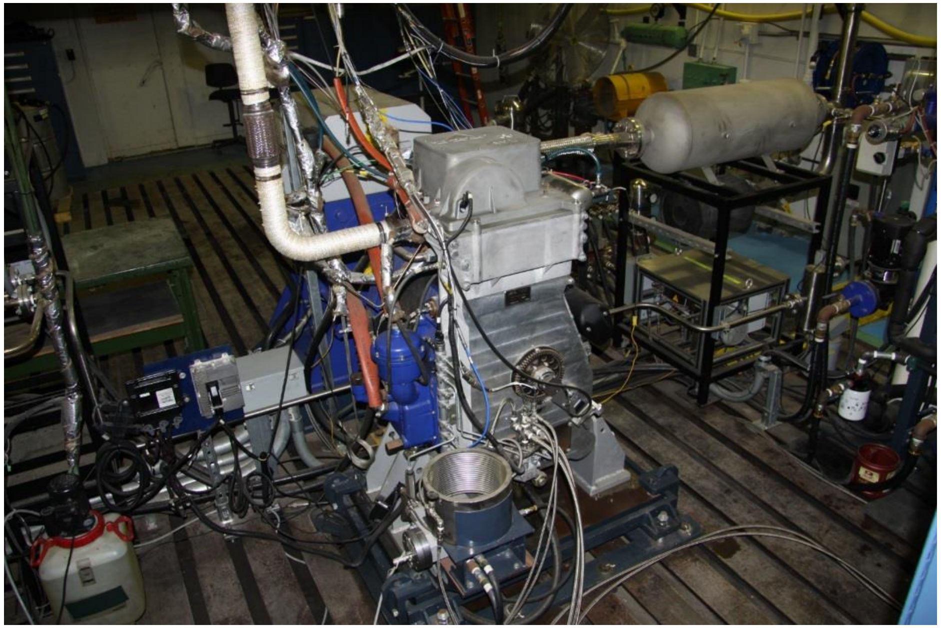
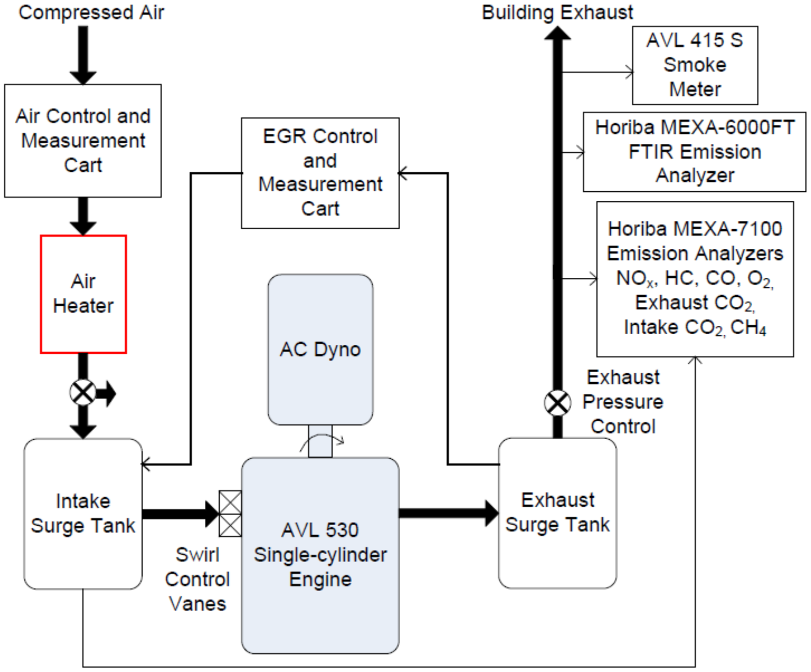
[1] Schihl, Gingrich, and Hoogterp, 2015

EXPERIMENTAL SETUP:
B212 CELL 7 SINGLE-CYLINDER ENGINE

Displacement (l)	**1.49**
Bore (mm)	122
Stroke (mm)	128
Common Rail Pressure (max) (bar)	2000
Number of Valves	4
Swirl Ratio (variable)	0-3.5
Peak Firing Pressure (bar)	250





Compressed Air

Air Control and Measurement Cart

Air Heater

EGR Control and Measurement Cart

AC Dyno

Intake Surge Tank

Swirl Control Vanes

AVL 530 Single-cylinder Engine

Exhaust Surge Tank

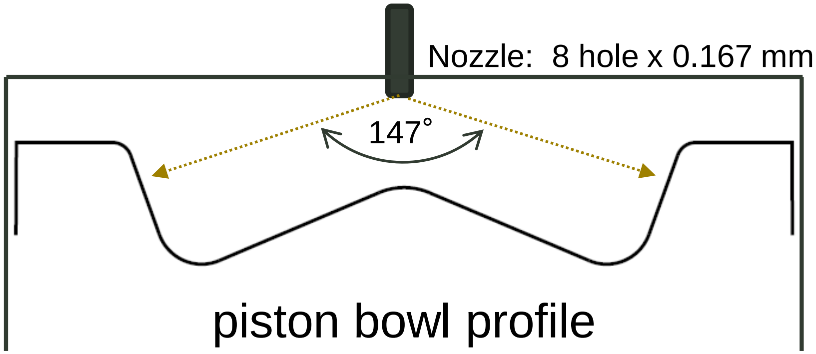
Exhaust Pressure Control

Building Exhaust

AVL 415 S Smoke Meter

Horiba MEXA-6000FT FTIR Emission Analyzer

Horiba MEXA-7100 Emission Analyzers NO_x, HC, CO, O_2, Exhaust CO_2, Intake CO_2, CH_4



FUEL PROPERTIES

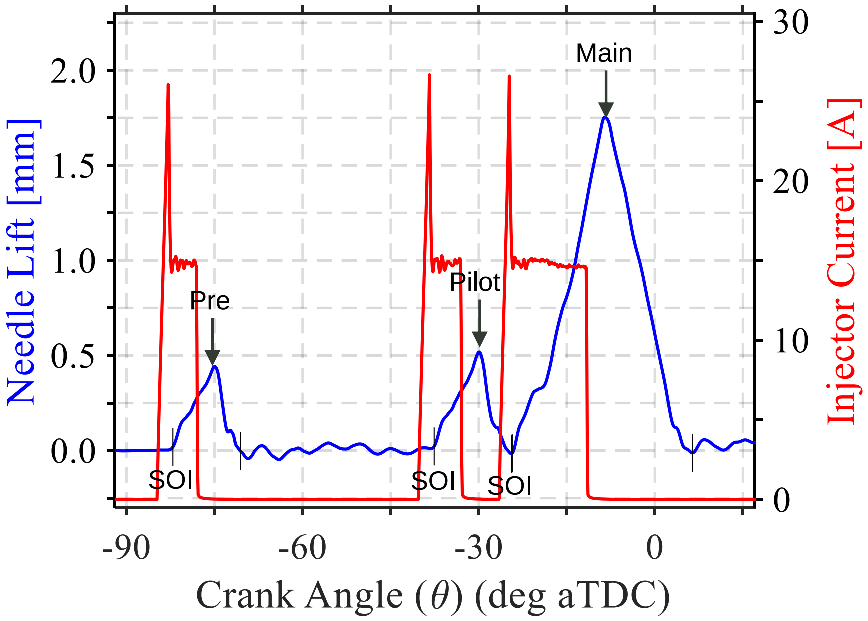
Fuel type		F-24 (procured locally)	Sasol IPK (POSF 7629)	Spec Limits (Blended fuel)
DCN	[-]	42	31	≥ 40 (MIL-DTL-83133)
LHV	[MJ/kg]	43.0	43.7	≥ 42.8
Density @ 15°C	[kg/m^3]	816	761	775 – 840
MW[2]	[kg/kmol]	154	149	
H/C	[-]	1.919	1.868	
Aromatics	[vol %]	15	1	≤ 25
Olefins	[vol %]	2.4	3.4	
Saturates	[vol %]	82.9	95.2	
Viscosity @ 40°C	[mm^2/s]	1.475	1.129	≤ 8 @ -20°C
Lubricity	[mm]	0.54	0.59	≤ 0.85
Distillation, T10	[°C]	189	165	≤ 205
Distillation, FBP	[°C]	264	228	≤ 300

[2] Zhu, et al., 2014

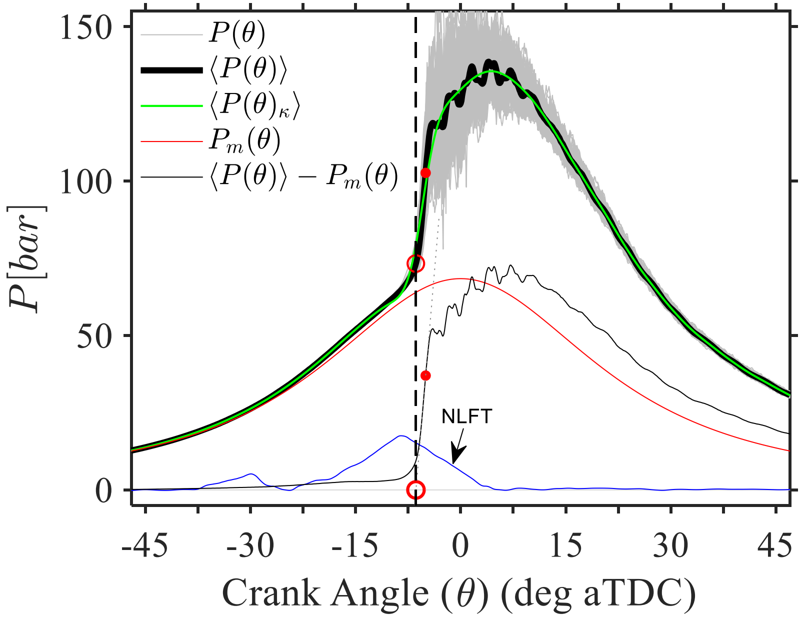
IGNITION DELAY, τ_{ign}

$$\tau_{ign} = \tau_{phys} + \tau_{chem}$$

- τ_{ign} defined as time duration between a) *start* of main fuel injection and b) *start* of combustion



- Start of injection (SOI) determined from injector needle lift (NLFT) sensor data



- Start of combustion (SOC) determined from extrapolation of the maximum slope of the pressure rise due to combustion to the zero crossing point[3], where:

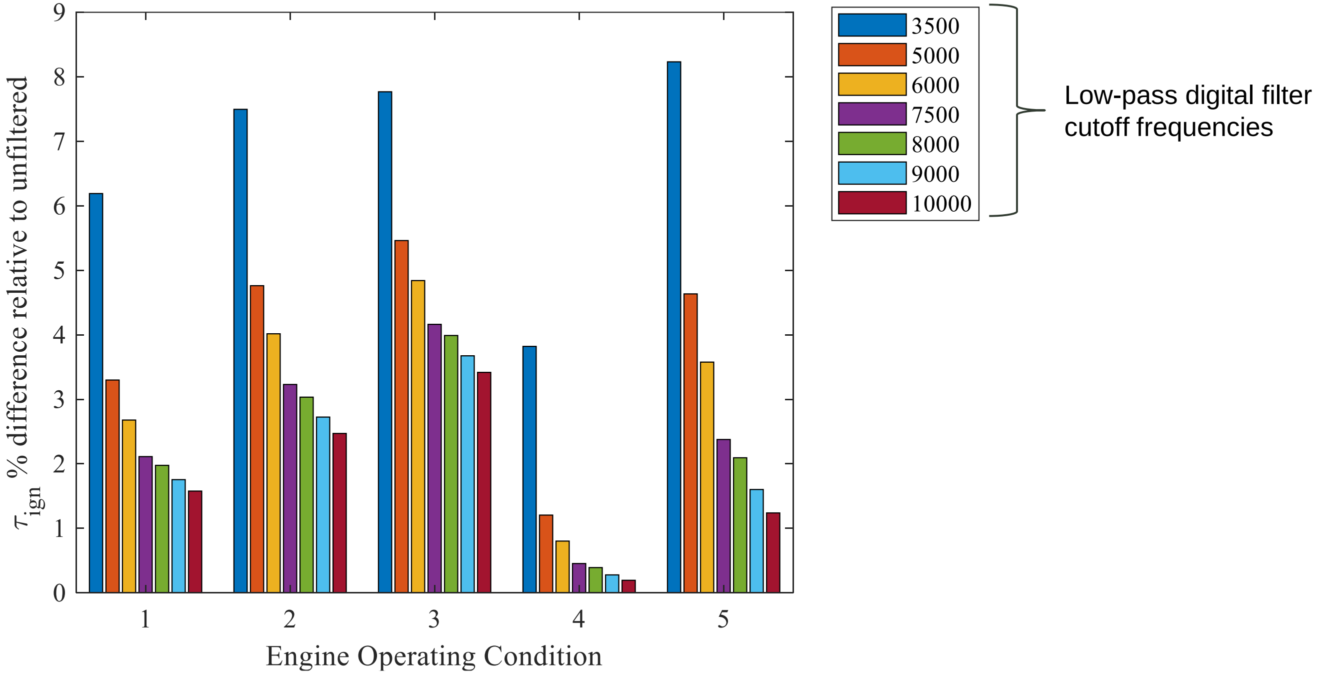
Pressure Rise: $\langle P(\theta)\rangle - P_m(\theta)$

Motored Pressure: $P_m(\theta) = P_{IVC} \cdot \left(\frac{V_{IVC}}{V(\theta)}\right)^{\gamma}$

[3] Rothamer and Murphy, 2013

FILTERING

- Pressure data often requires filtering due to excitation of resonance modes within the cylinder[4]
- Filter with caution when measuring ignition delay
- For this work, ensemble-averaged pressure data were not filtered



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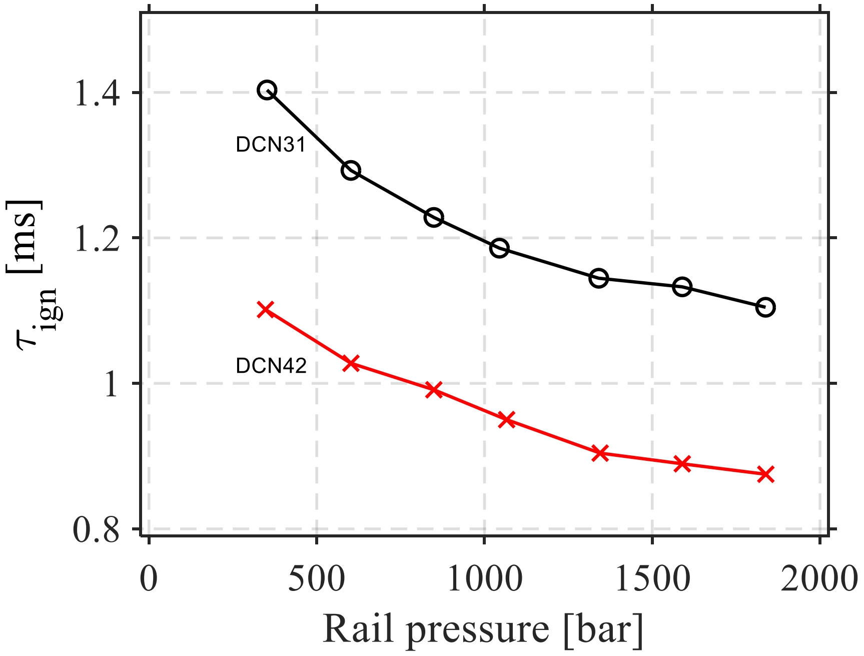
[4] Hickling, et al., 1983

RESULTS

COMMON RAIL PRESSURE (1 OF 3)

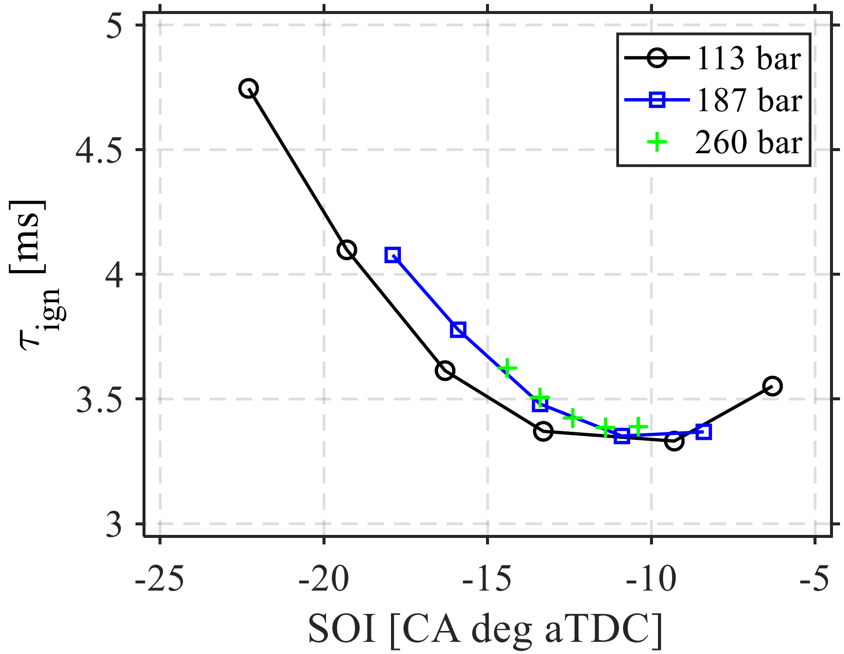
- At most engine operating conditions, higher injection pressures result in an asymptotic decrease in the physical delay time τ_{phys} (spray break-up, vaporization, and mixing processes)



Operating condition: CN31 fuel, 1700 RPM, single injection, constant SOI command (SOIC) timing (16 deg bTDC), constant fuel mass

COMMON RAIL PRESSURE (2 OF 3)

- Higher injection pressures with low-cetane fuel are a *detriment* to engine operation at low speed/load:
  - Slightly increases τ_{ign}
  - Decreases the crank-angle window of viable injection timings (limited by misfires and excessive HC emissions)

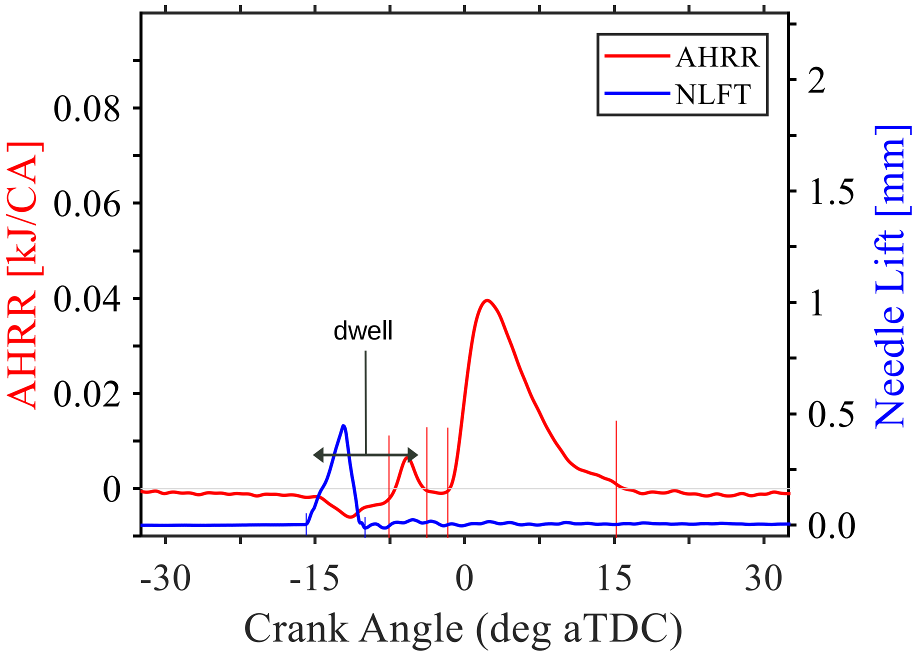


Operating condition: CN31 fuel, 750 RPM, single injection, constant fuel mass

COMMON RAIL PRESSURE (3 OF 3)

- Explanation: high injection pressure with low-cetane fuel at low speed/load results in an over-mixed condition
  - Positive ignition dwell – start of combustion occurs after *end* of injection
  - No longer a diffusion-controlled combustion regime

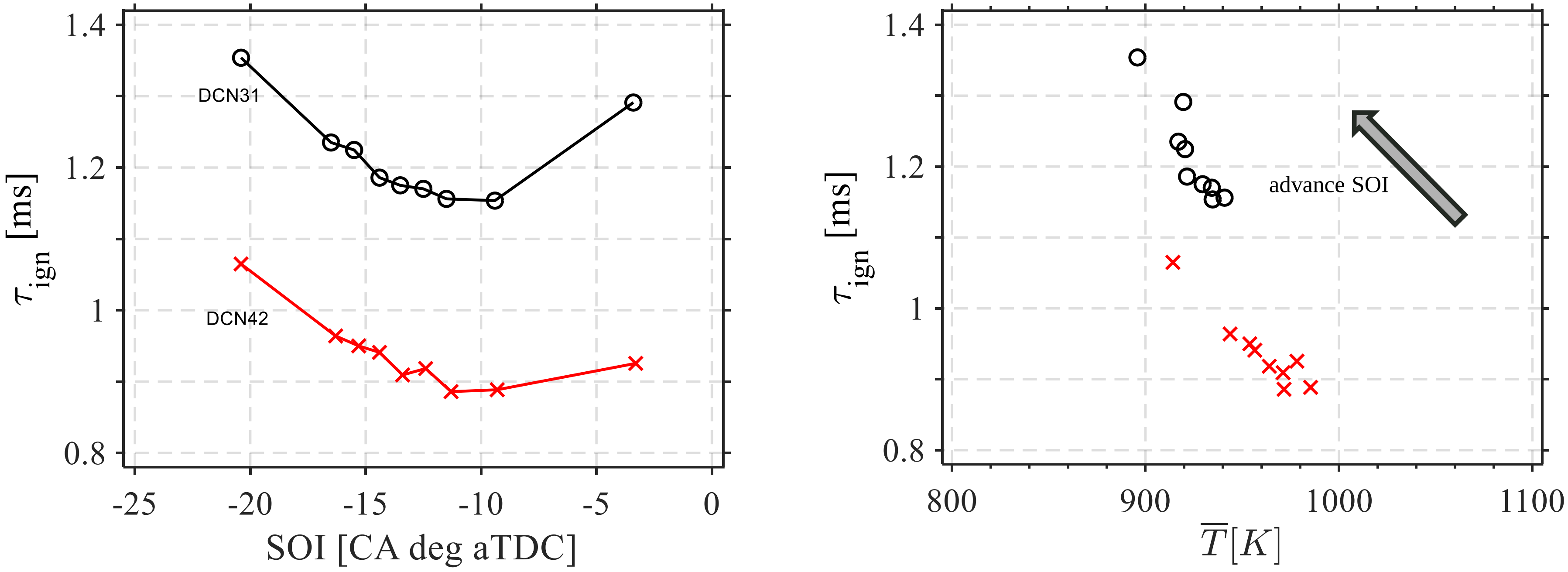
Apparent heat release rate (AHRR)



Operating condition (idle case): CN31 fuel, 750 RPM, single injection, SOIC timing 16.5 deg bTDC, P_{rail} 325 bar

INJECTION TIMING (1 OF 2)

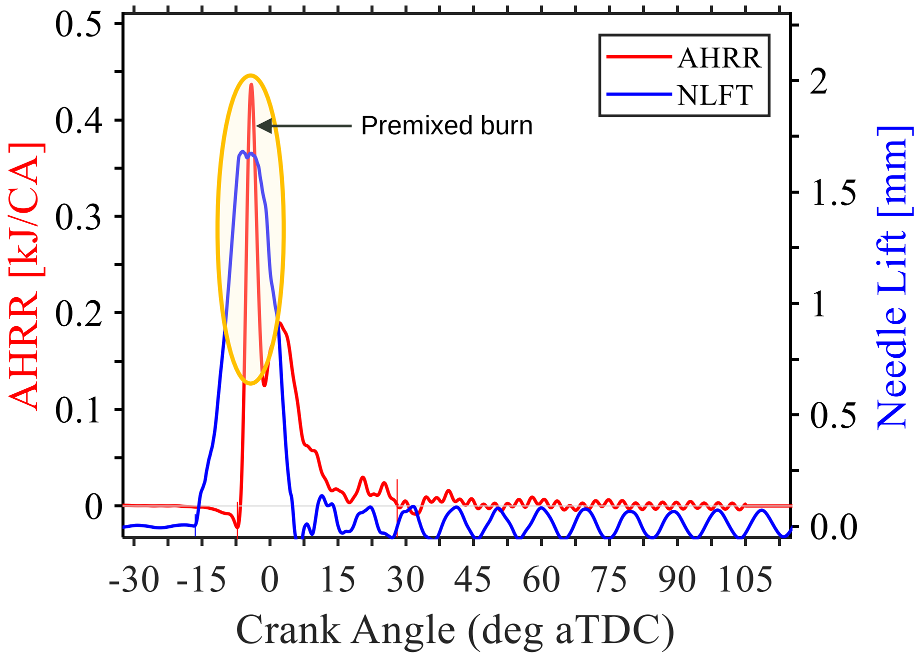
- Advancing or retarding the injection timing controls combustion phasing with limited influence on τ_{ign} by changing the thermodynamic conditions during the injection and ignition processes
  - Arrenhius equation: $\tau_{chem} \propto \boldsymbol{\rho}^{-0.8} e^{(E_A/RT)}$



Operating condition: 1700 RPM, P_{rail} 1200 bar, constant fuel mass

INJECTION TIMING (2 OF 2)

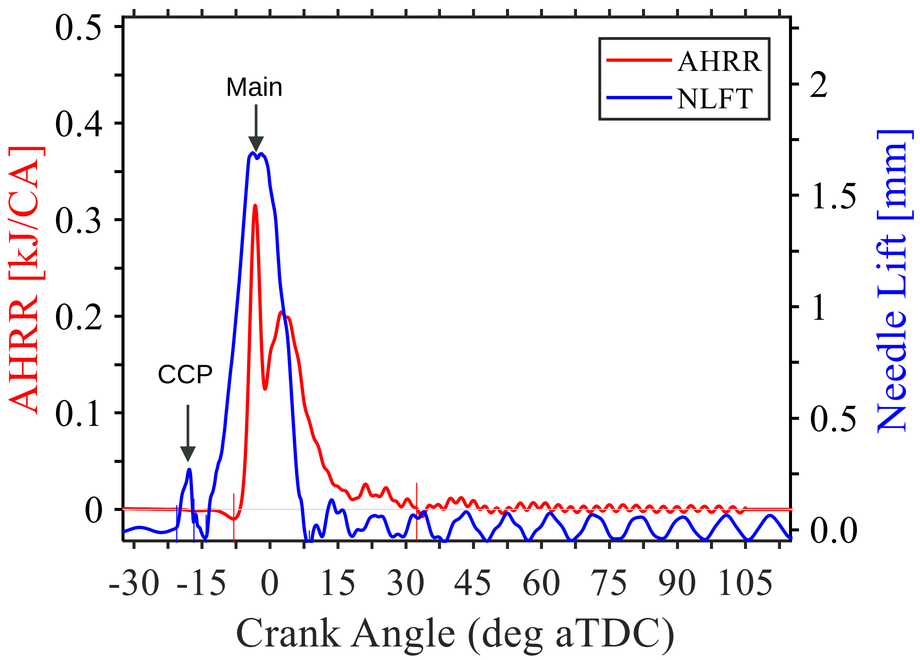
- Injection timing alone does not address the shape of the heat release profile for operating conditions with a single injection strategy and long τ_{ign}
  - Large premixed burn spike in the apparent heat release rate (AHRR) (undesirable combustion noise)
  - High cylinder pressure rise rates (excessive stresses)



Operating condition: CN31 fuel, 1700 RPM, P_{rail} 1200 bar, SOI timing 18 deg bTDC

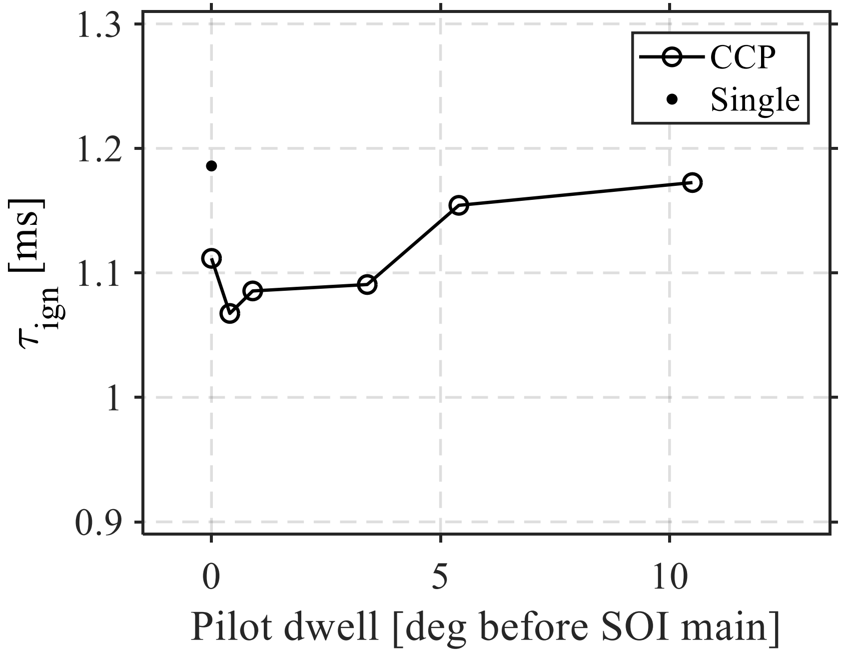
CLOSE-COUPLED PILOT (CCP) INJECTION (1 OF 4)

- CCP fuel injection strategy: inject a small pulse of fuel prior to the main injection event
  - Common strategy in commercial diesel engine calibrations to control emissions and combustion noise
  - When using a low-cetane fuel, the goal of a CCP is to reduce τ_{ign} by inducing a small heat release prior to the main injection event



CCP INJECTION (2 OF 4)

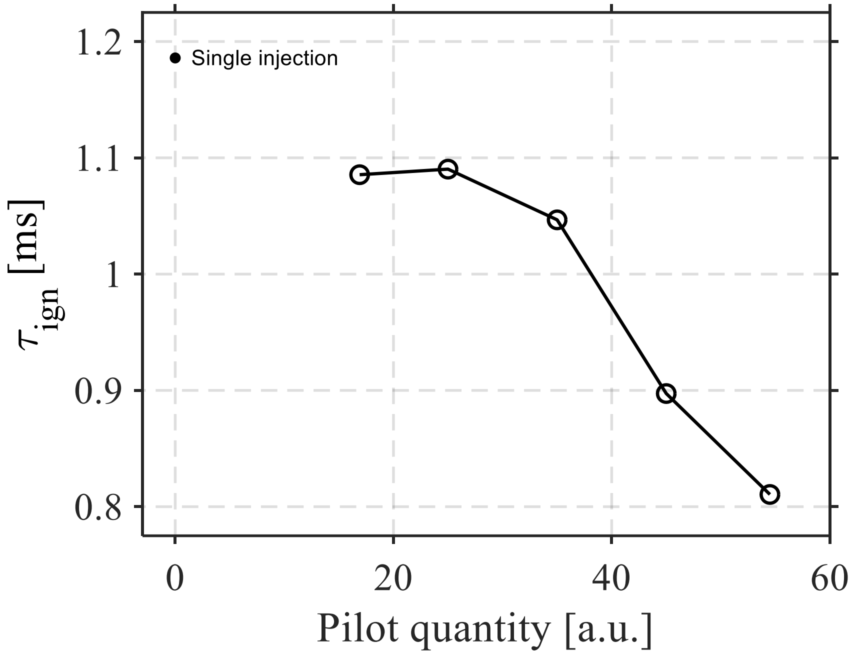
- Optimize CCP timing relative to a constant main injection SOI
  - Pilot SOI: parametric evaluation of the injection dwell period between the end of CCP injection and start of main injection



Operating condition: CN31 fuel, 1700 RPM, constant main SOIC timing (16 deg bTDC), P_{rail} 1200 bar, constant total fuel mass flow rate

CCP INJECTION (3 OF 4)

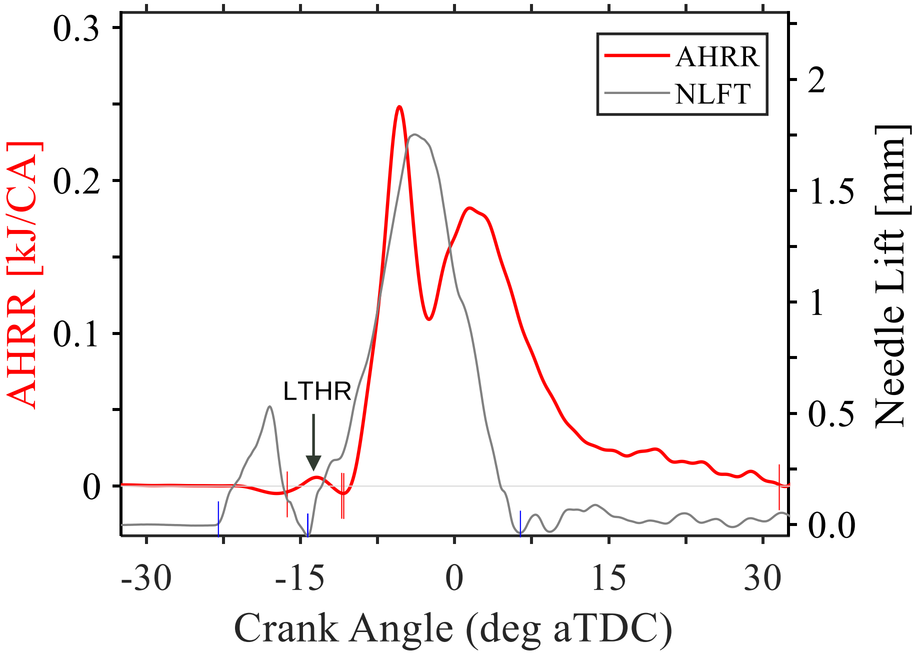
- Optimize CCP injection duration at constant total fuel flow
  - Pilot mass: parametric evaluation of the proportion of fuel mass in the CCP injection while holding total injected fuel per cycle constant



Operating condition: CN31 fuel, 1700 RPM, constant main SOIC timing (16 deg bTDC) and constant CCP dwell (5 deg before main SOIC), P_{rail} 1200 bar, constant total fuel mass flow rate

CCP INJECTION (4 OF 4)

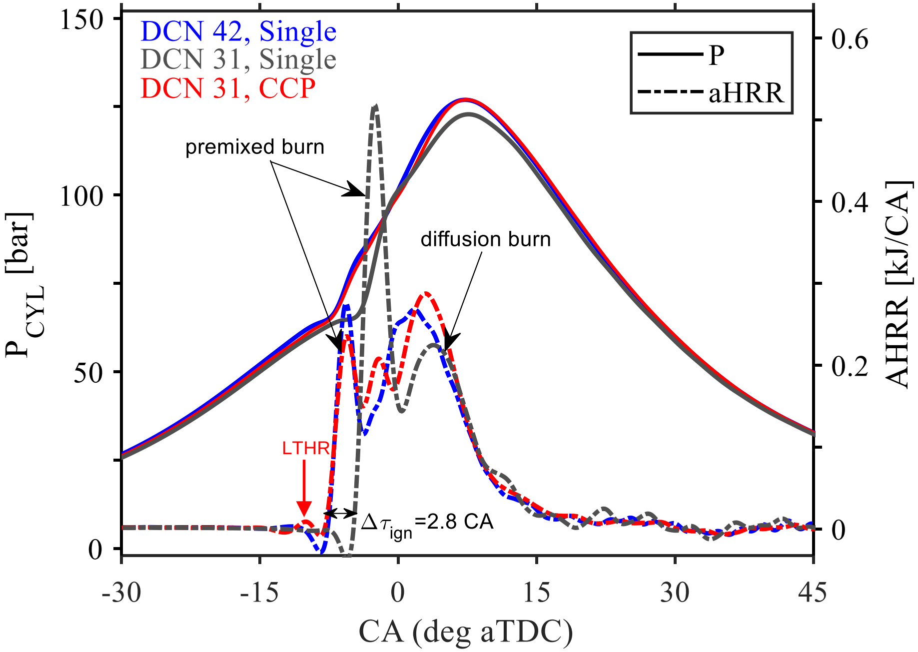
- As pilot fuel quantity increases, the negative temperature coefficient (NTC) behavior of the fuel becomes more active (low-temperature heat release)



Operating condition: CN31 fuel, 1700 RPM, main SOIC timing (16 deg bTDC) and CCP dwell 5 deg before main SOIC, P_{rail} 1200 bar

OPTIMIZING CCP PARAMETERS

- Optimizing the CCP strategy (CCP timing and dwell) results in significant changes to the heat release profile of the low-cetane fuel, giving premixed and diffusion burn phases that nearly match those of the F-24 specification fuel (DCN 42)



Operating condition: 1700 RPM

CONCLUSIONS

- A close-coupled pilot injection is an effective strategy to shorten τ_{ign} of a low-cetane fuel (DCN < 40), reshaping the premixed and diffusion burn phases of the heat release rate to resemble those of a conventional fuel (DCN ≥ 40).
- Low rail pressure (< 400 bar) with a single-injection strategy prevents combustion misfires at low-load engine operating conditions, such as idle and tactical idle

FUTURE WORK

- Evaluate the CCP injection strategy at a broader range of engine speeds/loads.
- Quantify the rate of injection and fuel mass in the pilot and main injection events.
- Investigate the close-coupled pilot injection strategy with an even lower cetane number fuel, such as an isobutanol-derived alcohol-to-jet synthetic paraffinic kerosene (DCN 17), pentamethylheptane (cetane reference value 16.3), or an ASTM D613-certified secondary reference fuel (cetane reference value 19-22)

Questions?