Heavy-Duty Natural Gas Engines, using pre-chambers to enable clean and efficient internal combustion engines

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Transportation

https://youtu.be/Yx1O7khdK48

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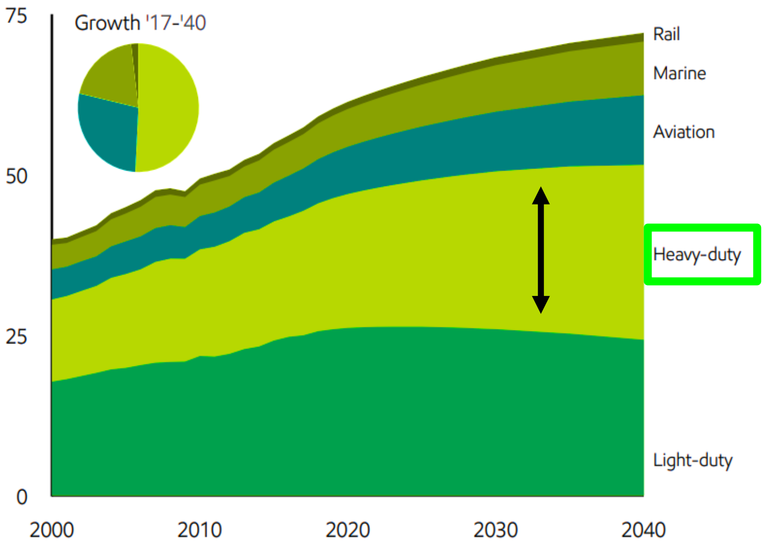
Introduction: Trucks are vital to a functioning economy

Transportation energy demand growth driven by commerce

Global sector demand – million oil-equivalent barrels per day (MBDOE) [1]



Challenges

Despite major improvements in internal combustion engine's efficiency and emissions in the last two decades, the heavy-duty sector continues to grow. Continuous improvements are necessary to mitigate environmental and health impacts.

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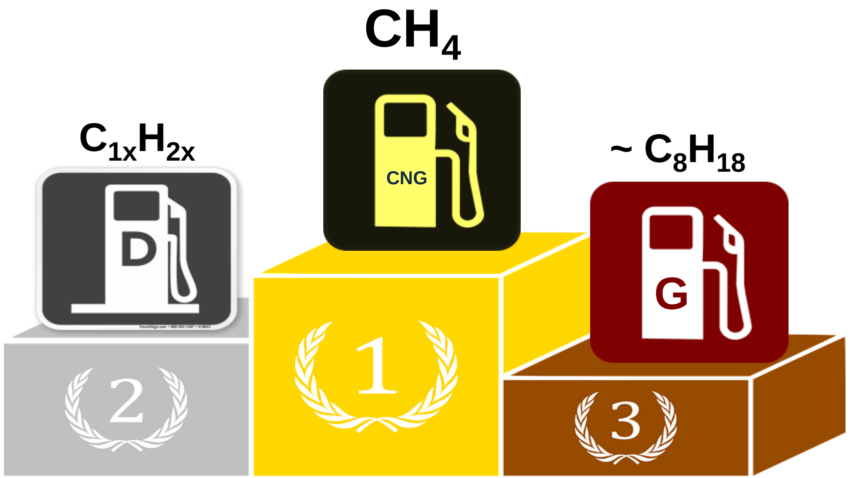
Objective: Perform Engine Research on Potential Paths to Improve Efficiency and Reduce Emissions



Current considerations:

Diesel engines can operate at **lean** and **highly-lean** air-to-fuel ratio while providing a significant thermodynamic advantage. Does not require an ignition system. Emissions from diesel engines require costly after-treatment system.

Gasoline (spark-based ignition) has practical limits to operate in heavy-duty engines → Autoignition

Natural gas has strong resistance to autoignition and requires an ignition system (e.g. spark plug, diesel pilot, laser, etc.). Low-carbon fuel → Cleanest of the 3 fuels

Pre-Chamber Spark Ignition (PCSI):

PCSI systems have shown the potential to **extend the natural gas engine lean/dilute combustion limit** while maintaining stable operation compared to conventional spark-plug-based combustion systems.

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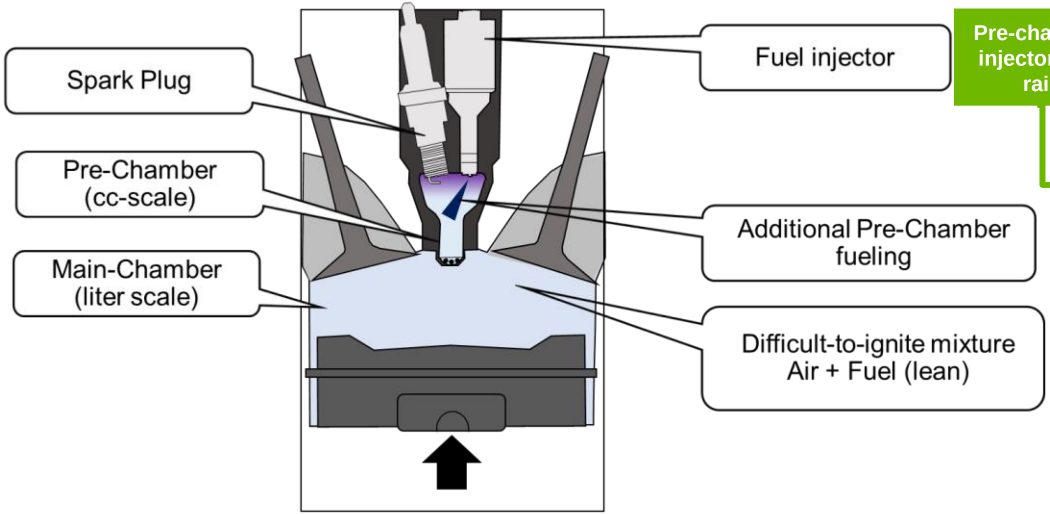
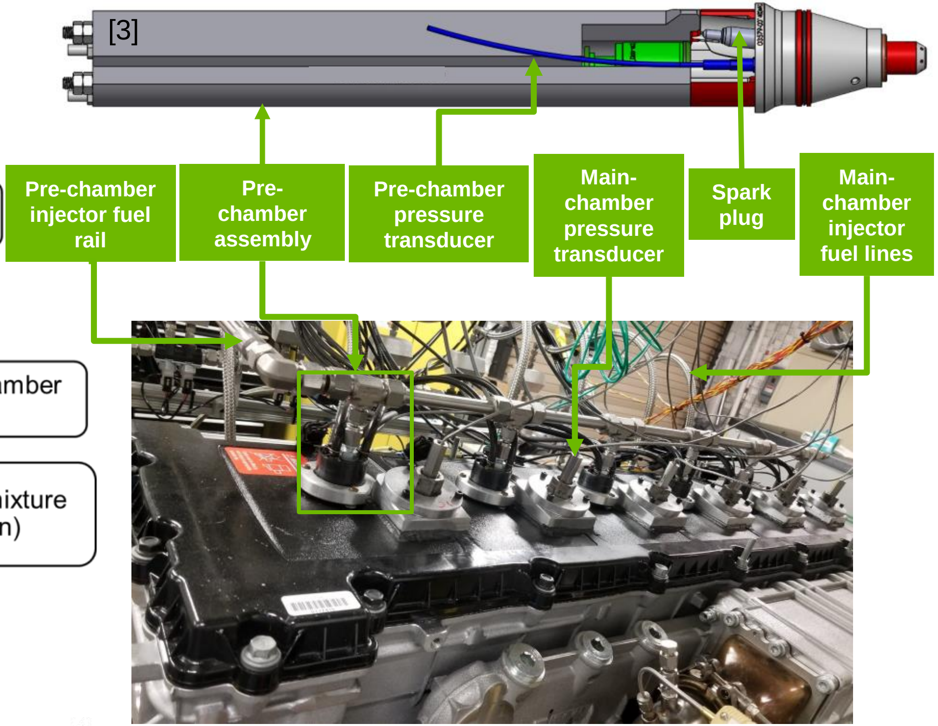
Method: Use pre-chambers to ignite difficult-to-ignite lean mixtures

Active PCSI systems are often designed to replace the diesel injectors with an assembly comprising of:





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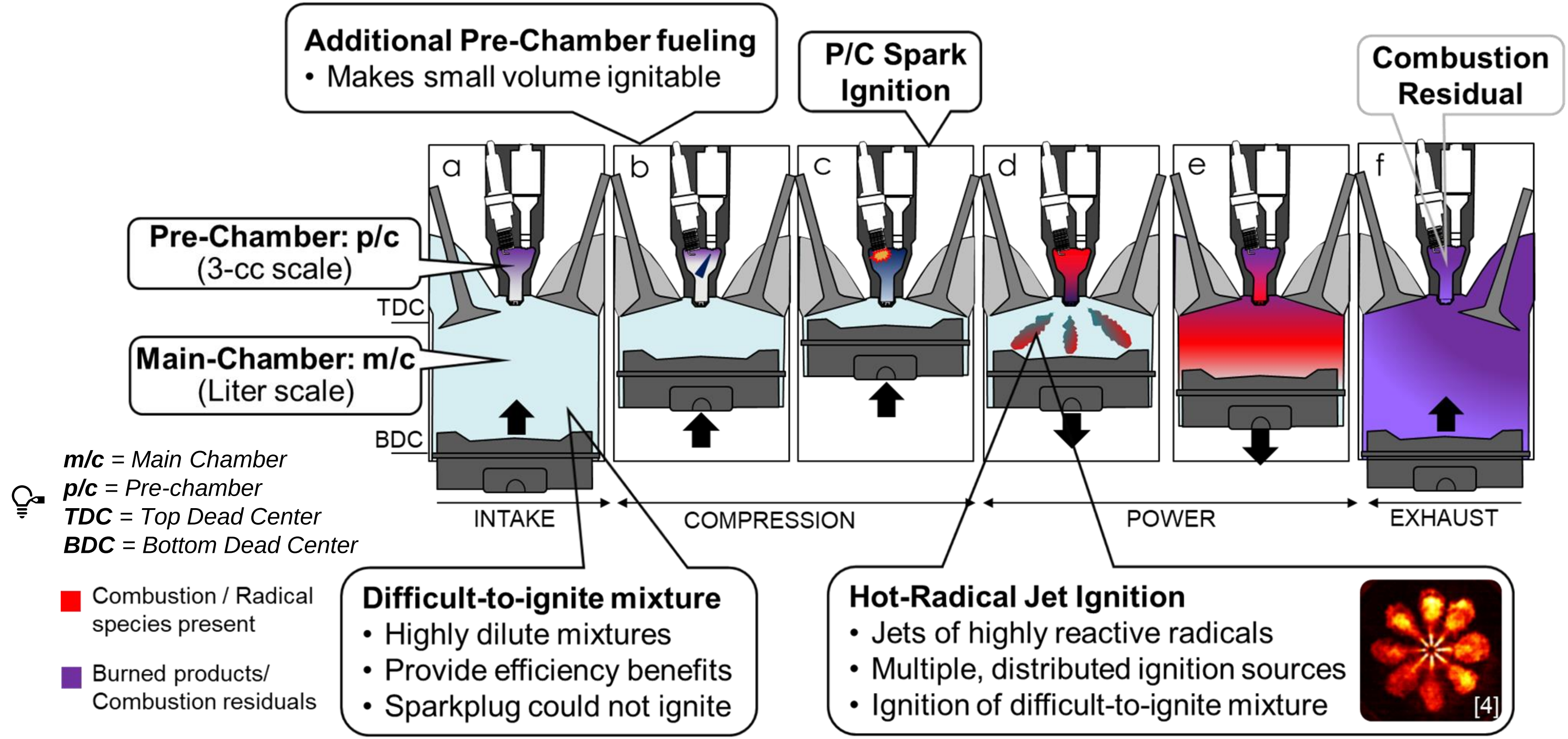
Method: Hot-Radical Jets Ignite the Main-Chamber Lean Mixture



Method: Production Derived Multi-Cylinder PCSI Engine

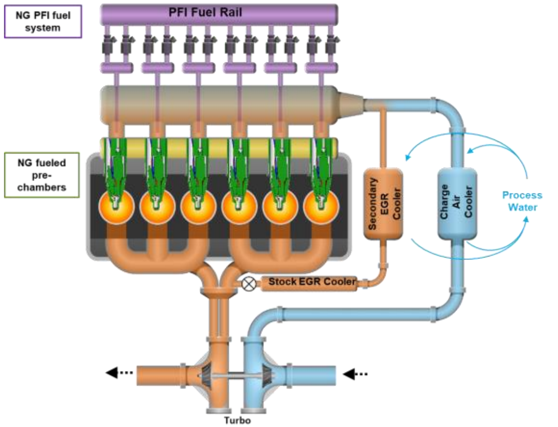
- **Engine:** Modified Daimler/Detroit DD13 (12.8 liters)
- **Pre-chamber System:** MAHLE – Prototype HD NG PCSI
  GDI injector – single hole, M8 Denso spark plug
- **Natural gas (NG) supplied to 2 independent fuel systems**
  PFI fuel rail: 7.5 bar
  PC fuel rail: 7.5 bar [Target 50- 100 bar]
- **Experiments Completed – 3.6 bar IMEPg** [results are fuel pressure limited]
  Unfueled multi-cylinder PCSI + Fueled multi-cylinder PCSI
  SI Baseline using custom spark inserts

IMEPg: *Gross indicated mean effective pressure (closed cycle performance)*

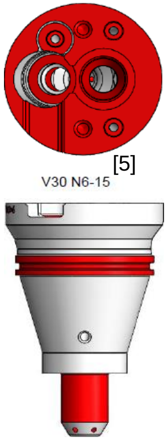
PC Volume [cm^3]	3.0
Nozzle diameter [mm]	1.5
Number of Nozzles [-]	6
Nozzle area/PC volume ratio [cm^{-1}]	0.0353
Included angle [º]	120

Number of cylinders	6
Bore [mm]	132
Stroke [mm]	156
Displacement [L]	2.13 / cyl
Compression ratio	18.3:1
Fueling system	
Main-Chamber	Port Fumigation
Pre-Chamber	Common rail
Natural Gas	Utility Piped NG (91% CH_4 avg.)

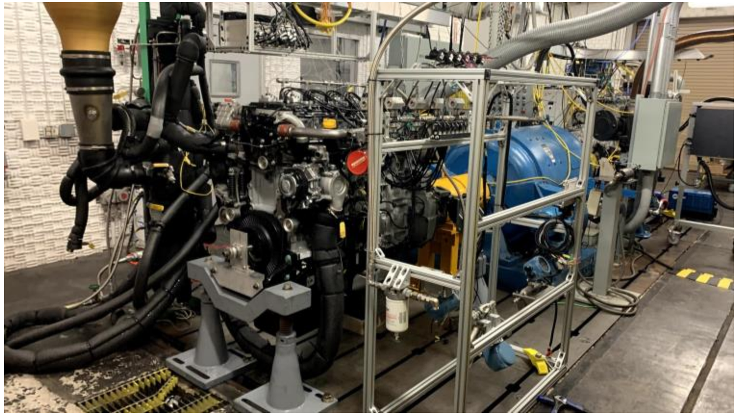
Engine setup schematic



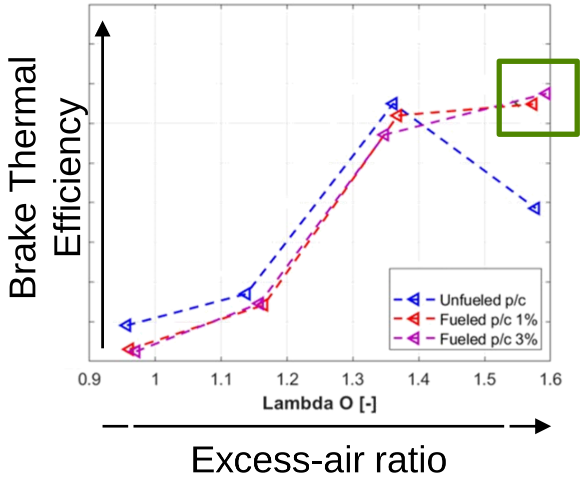
3D printed pre-chamber



Experimental setup at the ORNL National Transportation Research Center



Results: Injecting fuel in the pre-chamber improves efficiency at lean conditions



Fuel + air from the m/c is pushed in the p/c

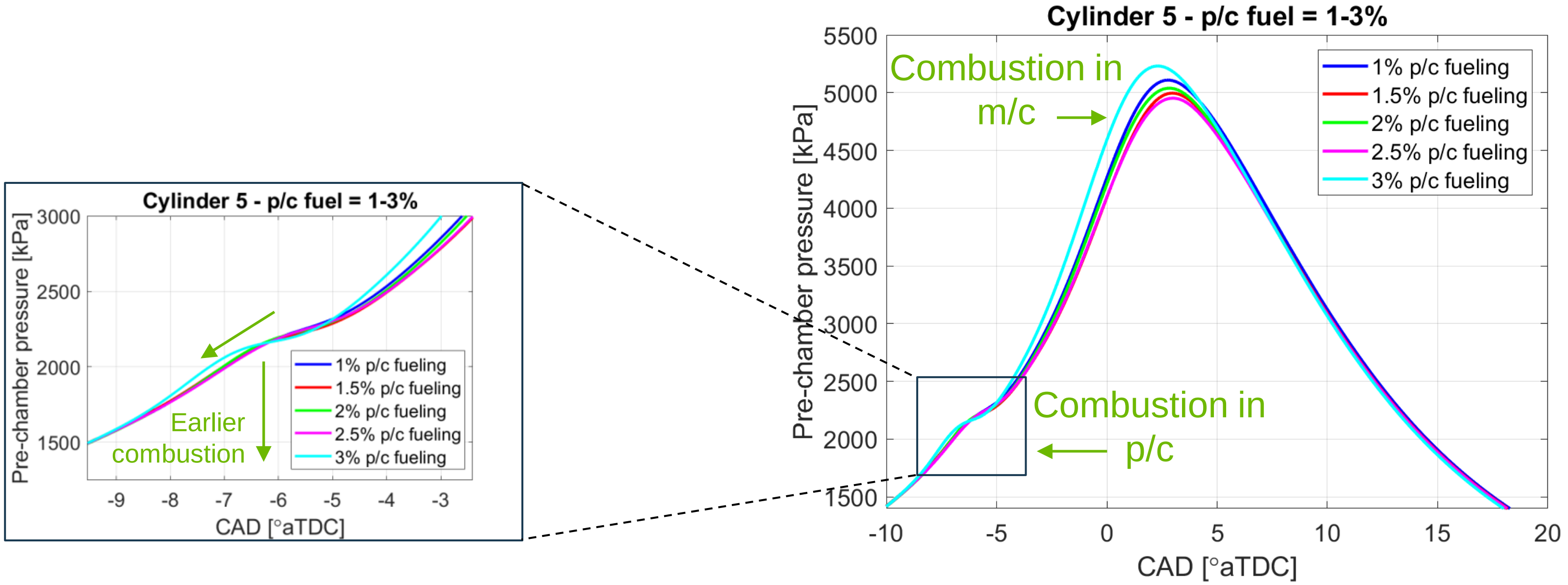
Additional fuel is injected in the p/c

		Unfueled PC		Fueled PC	
Engine speed	**rpm**	**1100 (matched mean piston speed)**			
Spark ignition timing	ºaTDCf	-14 to -23		-14 to -23	
Excess-air ratio (λ)	-	1.00	1.65	1.00	1.65*
Fuel ratio of PC/intake	%	-	-	1.0, 3.0*	
Engine load (IMEPg)	bar	3.6		3.6	

ºaTDC *= Crank angle degree after top dead center of firing (when the piston reaches the top of the combustion chamber and gases are fully compressed)*
Excess-air ratio: *λ >1 when the air to fuel balance is leaner than stoichiometric*

Further extension of the excess air ratio requires increased p/c fuel injection pressure (7.5 bar to ~50 bar)

Results: Increasing the quantity of fuel injected in the pre-chamber positively affects the main chamber combustion



1% to 3% of the total amount of fuel (m/c +p/c) was injected int the p/c → p/c became fuel rich while maintaining m/c fuel lean

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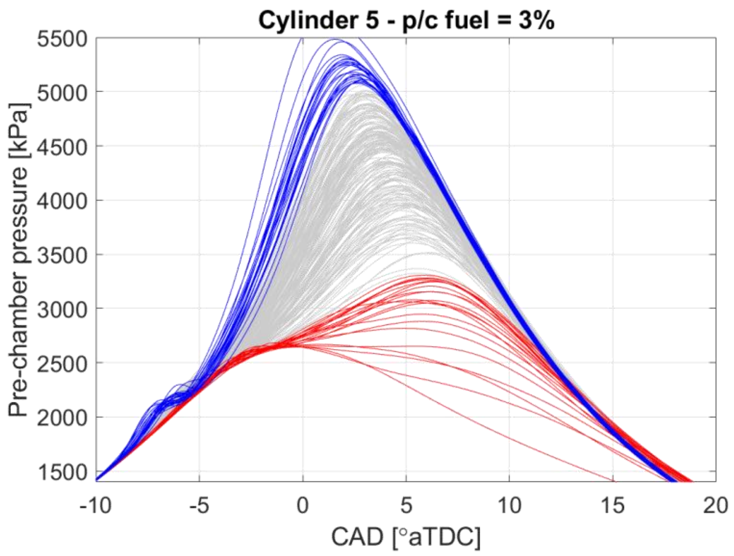
Results: Combustion stability in p/c affects combustion quality in m/c.



p/c ignites → good m/c combustion

p/c ignites late → poor m/c combustion quality

p/c does NOT ignite → m/c misfires

What are the fundamental elements of a stable p/c combustion?

Injection duration: is there fuel slippage out of the p/c if long duration?

Injection pressure: what is the appropriate ratio of fuel injection/background pressure to favor mixing?

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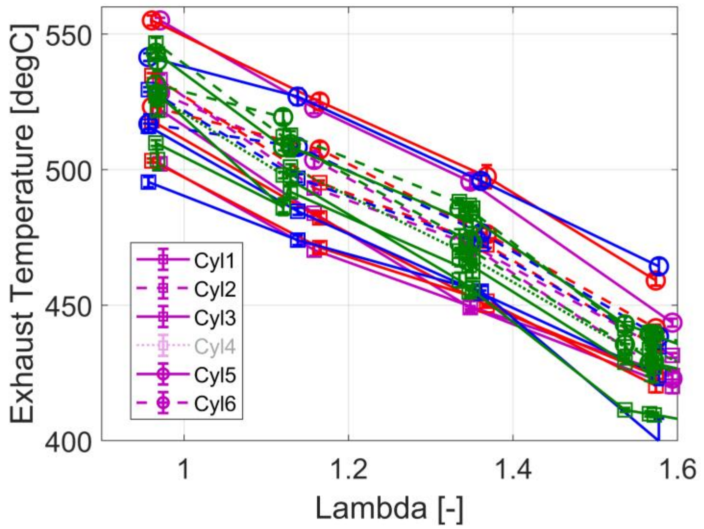
Conclusions

- Pre-Chamber Spark Ignition is a promising technology to improve the efficiency of heavy-duty natural gas engines

- Further research is needed to understand the fundamental aspects of the pre-chamber combustion to optimize the engine design and calibration

- Lean natural gas combustion causes exhaust temperatures to fall below the limits of operation of the current methane oxidation catalysts. Parallel efforts are conducted at ORNL to provide solutions to this challenge.

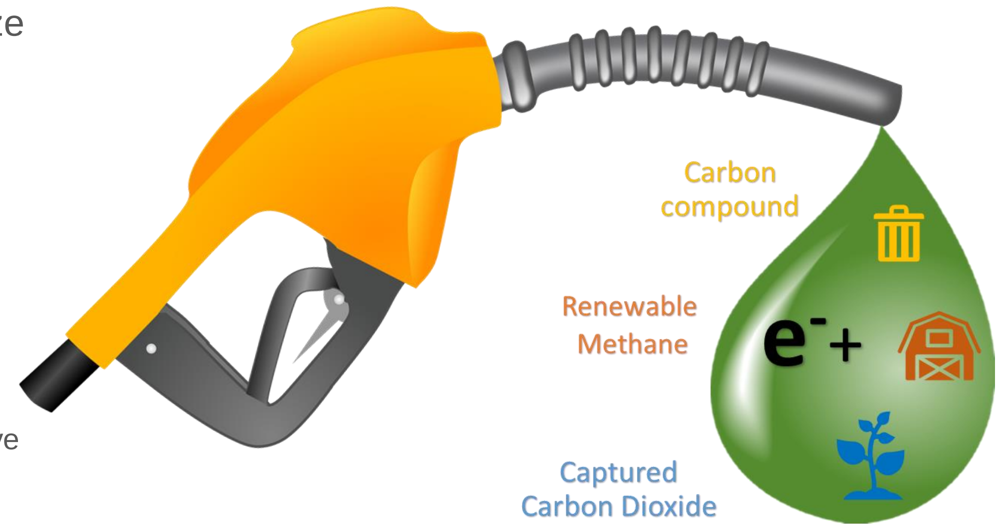
Exhaust temperatures fall with increased excess-air ratio



Future work: a pathway to net-zero carbon transportation?

- Complete experiments to quantify/characterize diesel-like efficiency:
  - increase injection pressure
  - investigate different injector and pre-chamber designs

- Investigate PCSI as a pathway to enable the use of net-zero carbon fuels (e-fuels) in HD transportation sector
  - e-Fuels require energy to be synthetized
  - many promising low-carbon fuels (methanol, ethers) have a high resistance to ignition
  - PCSI has the potential to facilitate the ignition of such fuels in heavy-duty engines



References

[1] ExxonMobil, “*2019 Outlook for Energy: A Perspective to 2040*”, 2019

[2] Environmental Protection Agency, “*EPA Emissions Standards for Heavy-Duty Highway Engines and Vehicles*”, 2016

[3] MAHLE Powertrain – ORNL MJI Heavy-Duty CNG (DD13 Conversion), 2018

[4] Musculus, M et al., “*Fundamental Advancements in Pre-Chamber Spark Ignition and Emissions Control for Natural Gas Engines: In-Cylinder Optical Imaging*”, Advanced Engine Crosscut Team Meeting, 2019.

[5] MAHLE Powertrain – ORNL MJI Heavy-Duty CNG (DD13 Conversion), 2018

Acknowledgments

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MAHLE Powertrain

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