Advanced Combustion Technology to Enable High Efficiency Clean Combustion

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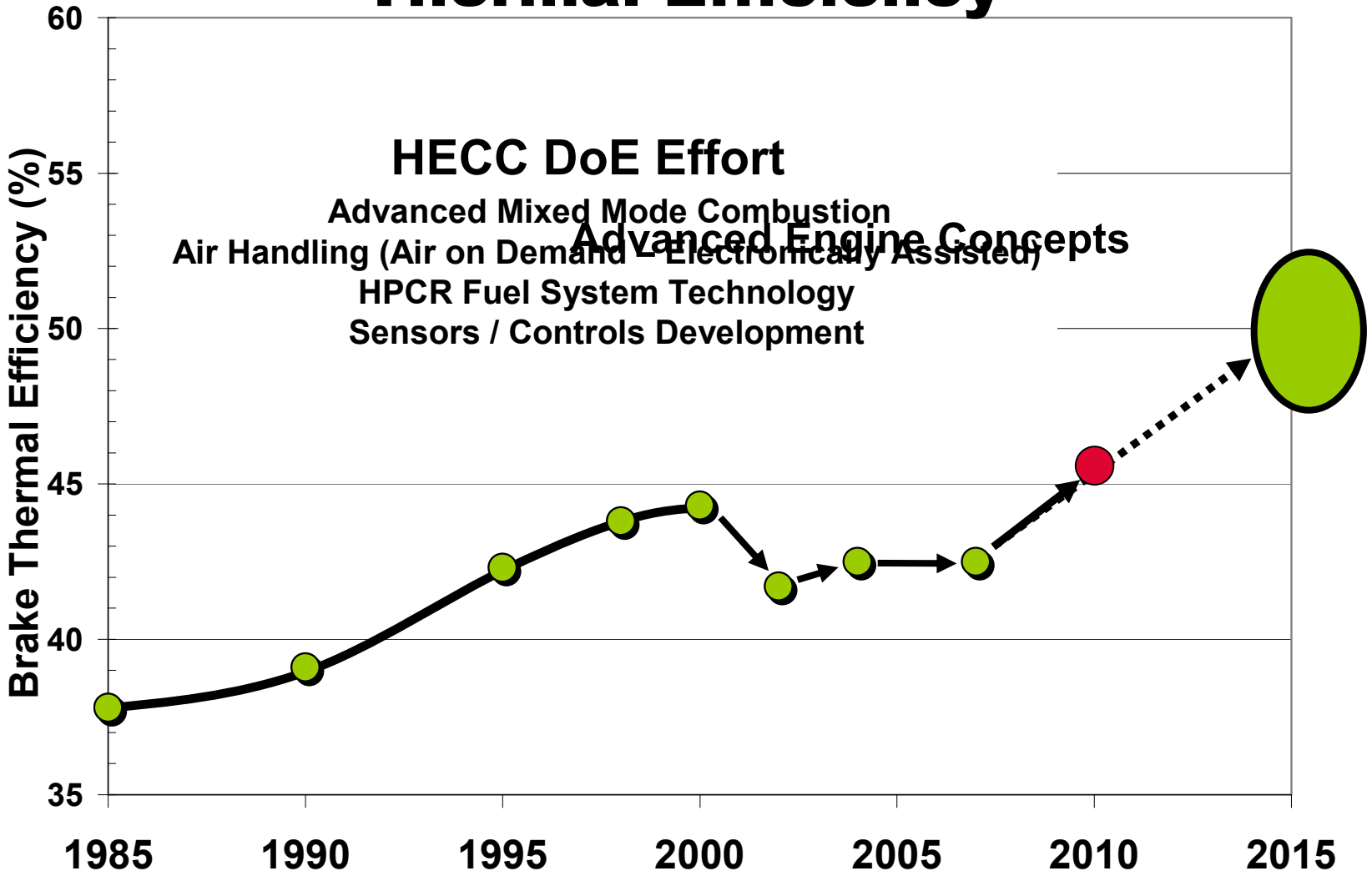
Product Attributes Influenced by Combustion Strategy

- Significant fuel economy improvement
  - Customer driven
  - Legislative initiatives
- Vehicle heat rejection
- Substantial increase in power density*
  - Hybrid powertrain integration
  - Vehicle electrification
  - Engine downsizing
- Cost

*Power Density = power/weight

Historical Perspective of HD Brake Thermal Efficiency



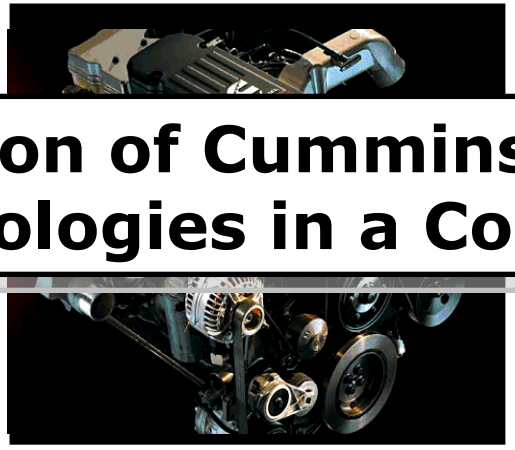
Technology Roadmap for Efficiency Improvement

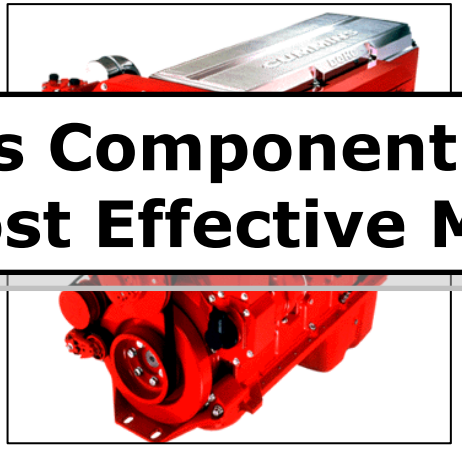
Variable Valve Actuation

Fuel System

Advanced LTC

Integration of Cummins Component Business Technologies in a Cost Effective Manner





6.7L ISB

15L ISB

EGR Loop

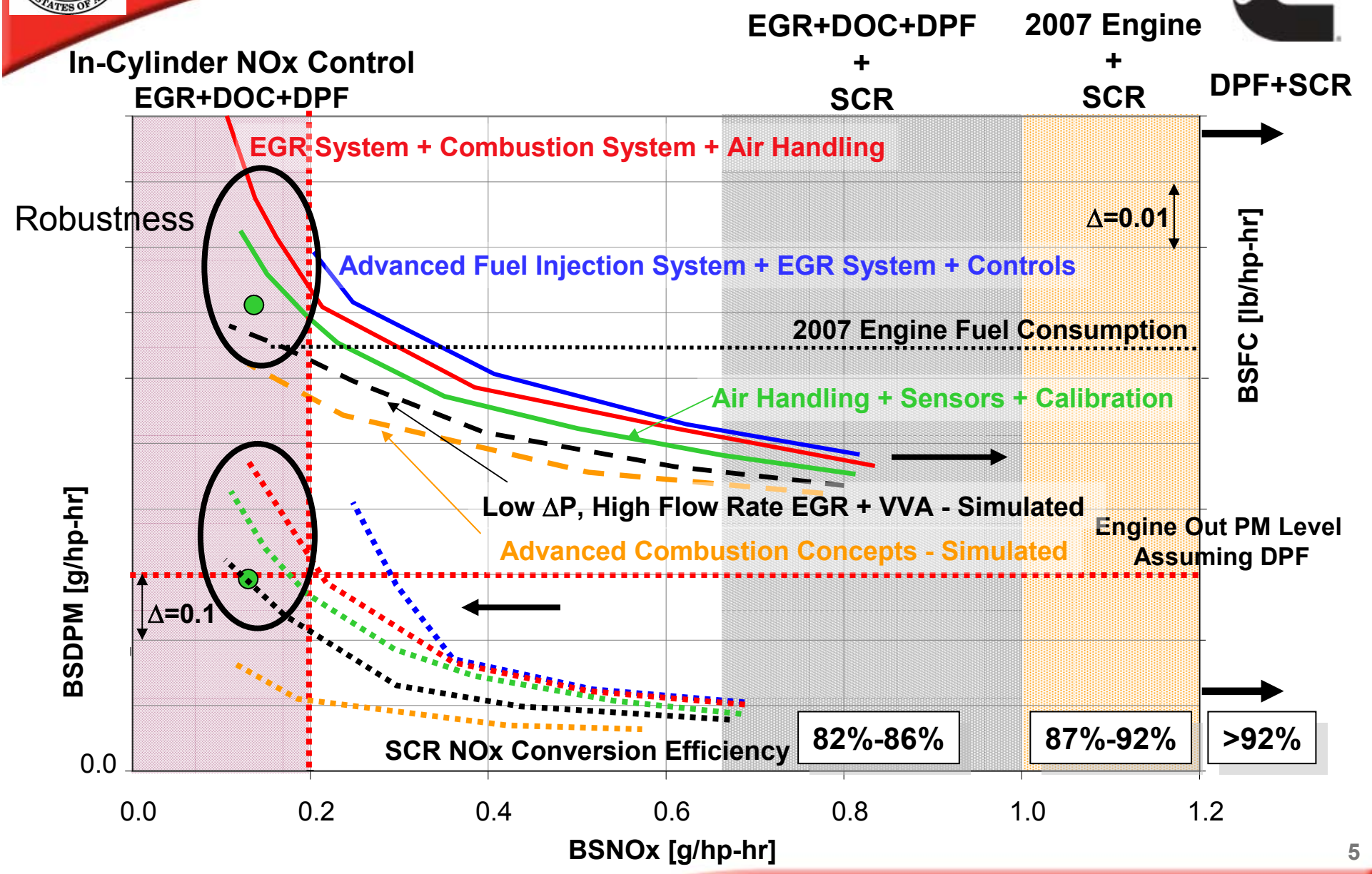
Electrically Driven Components

Turbo Technology

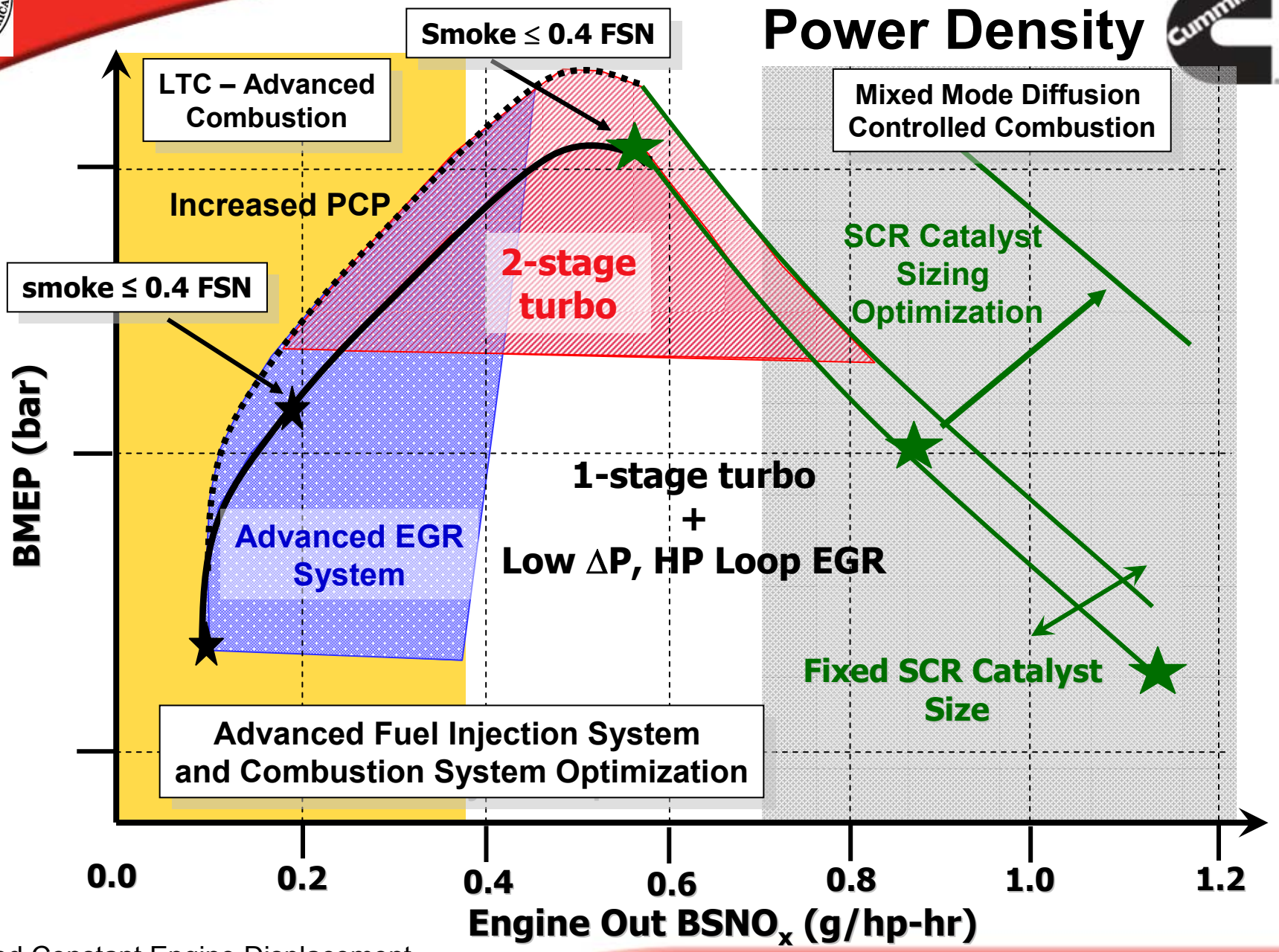
Aftertreatment

Hybrid/WHR

Achieving a Wide Range of Engine Out NOx Capability

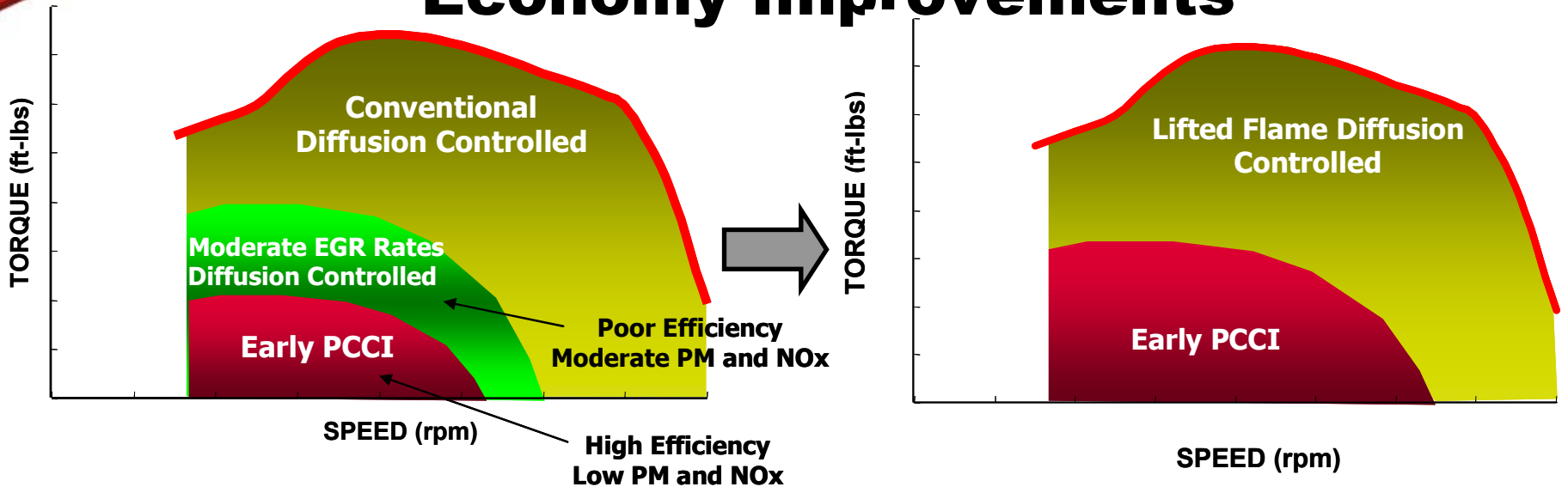


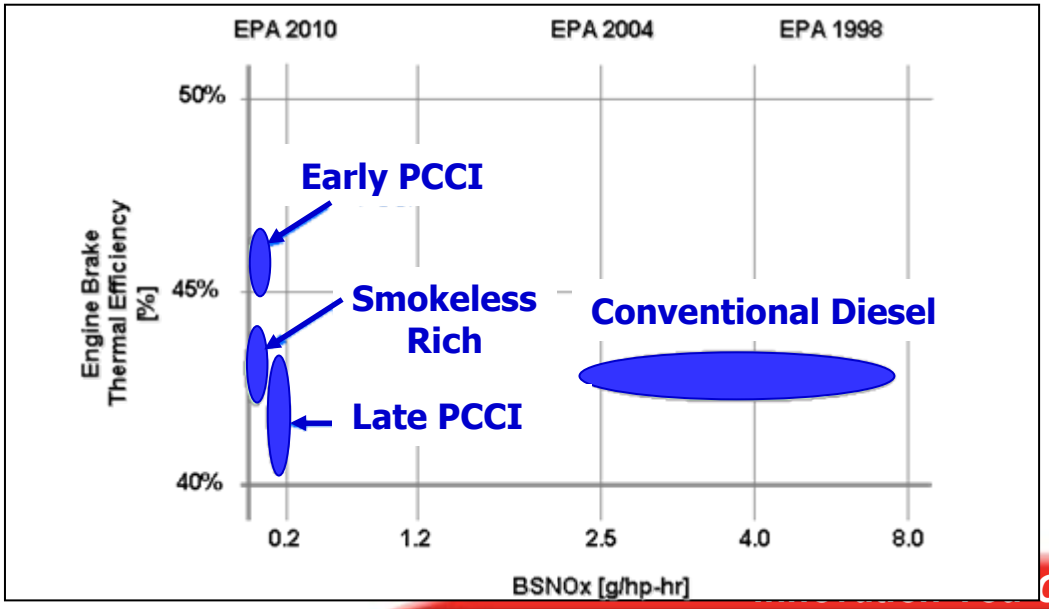
Power Density



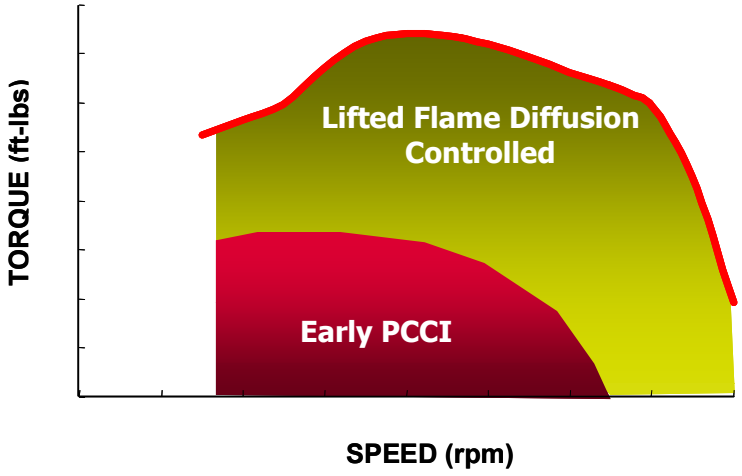
Assumed Constant Engine Displacement

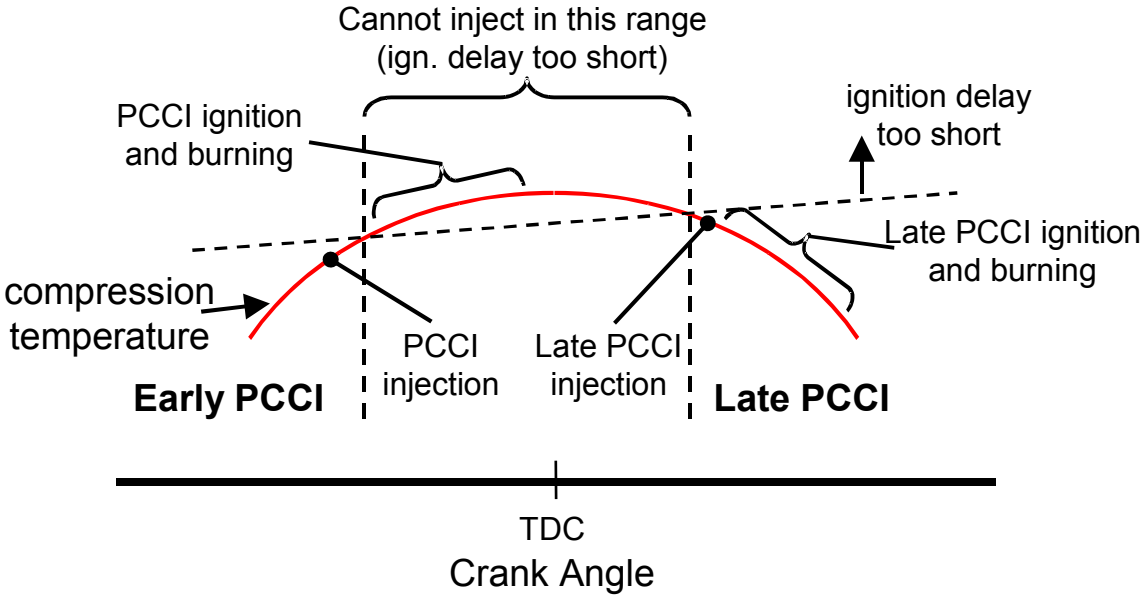
Combustion Strategy for Fuel Economy Improvements





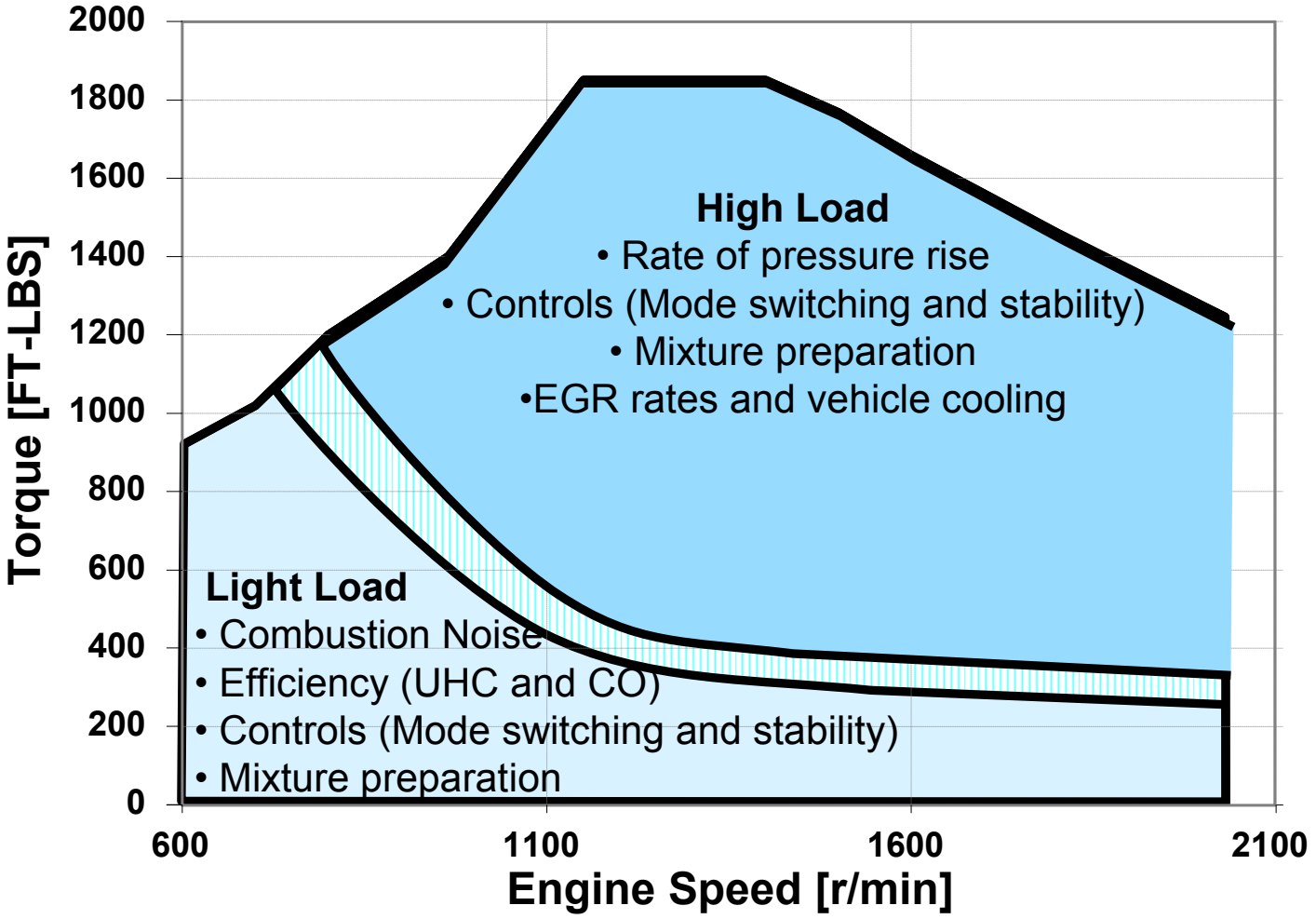
Extending the Range of Early PCCI



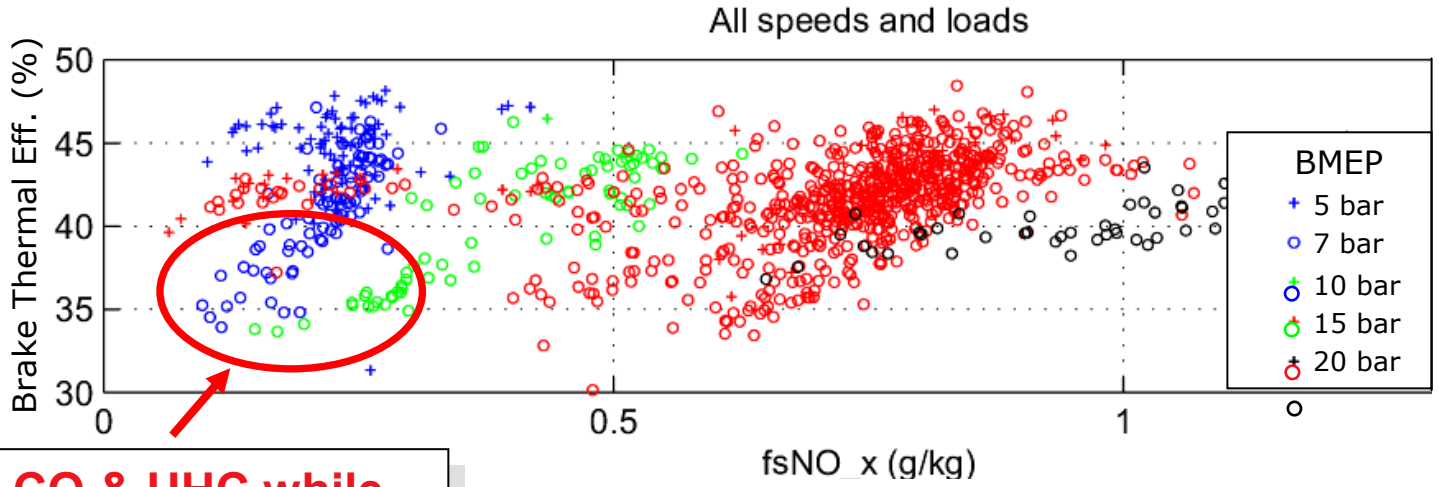


Mode	Advantages	Disadvantages
Early PCCI	- Good stability - Good fuel consumption	- High peak cyl. pressure - Limited BMEP - Noise - Higher cooled EGR rates
Late PCCI	- Low peak cyl. pressure - High BMEP capability (20 bar) - Low noise	- Narrow stability range - Higher fuel consumption - Needs combustion sensor

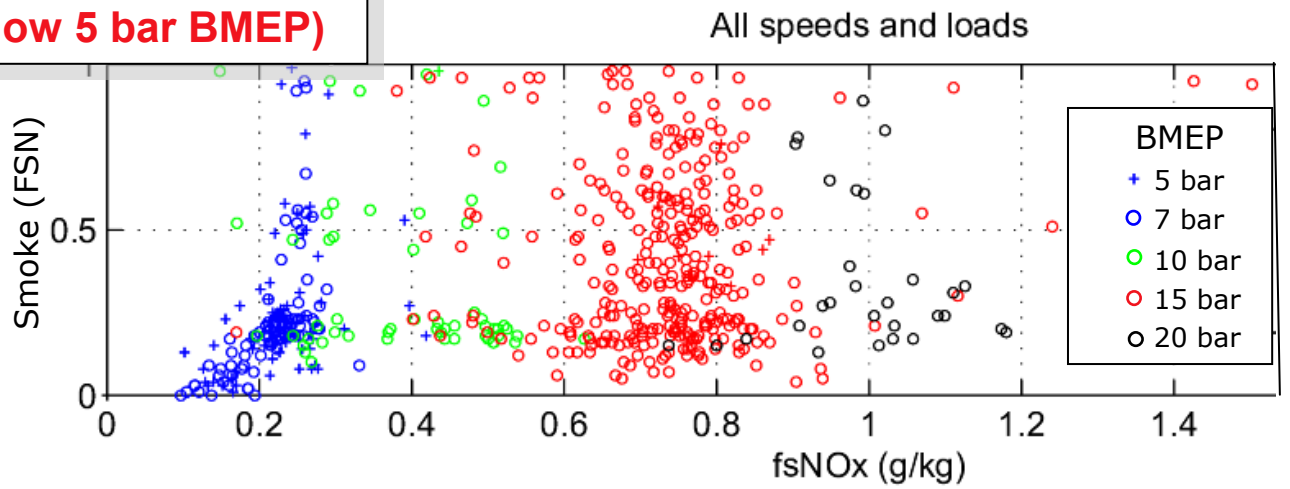
Challenges for Full Engine Operation in PCCI Combustion



Extending the Engine Operation Range of PCCI

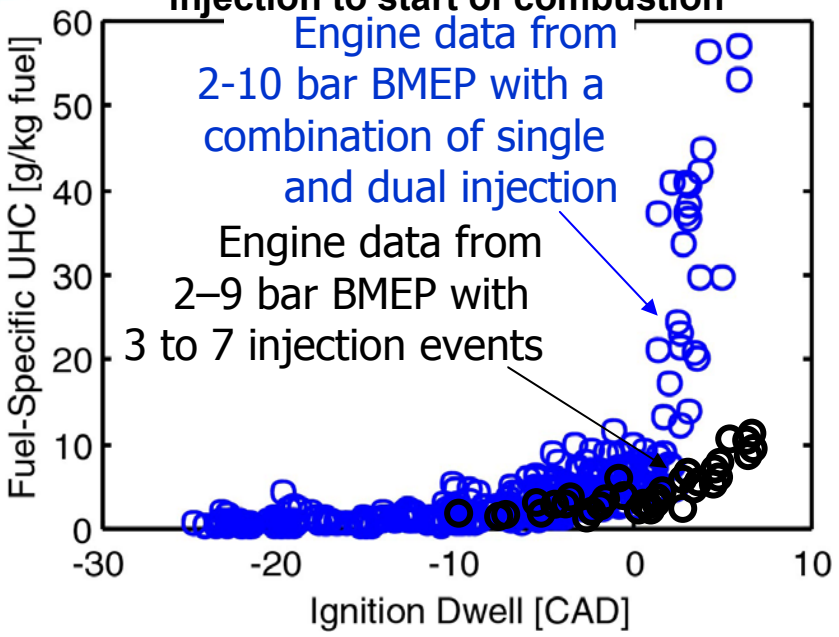


Reduce CO & UHC while maintaining acceptable NVH (especially below 5 bar BMEP)

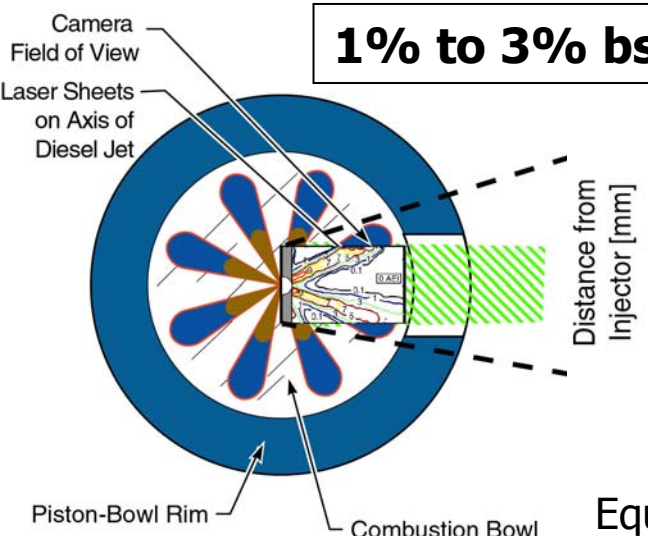


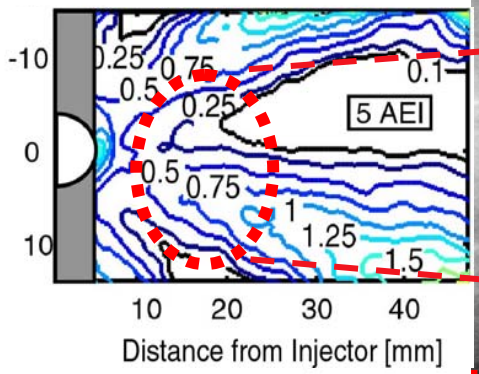
Combined Early and Late PCCI

Reducing HC and CO for Early PCCI Efficiency Improvement

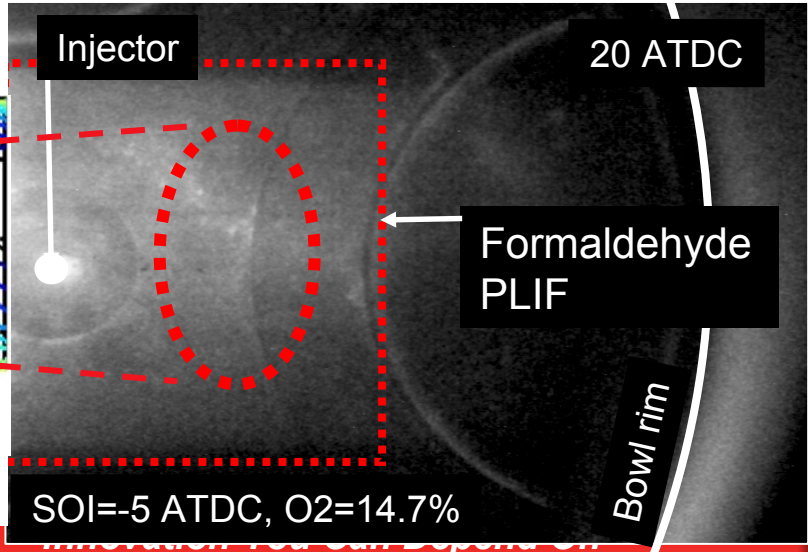


1% to 3% bsfc reduction





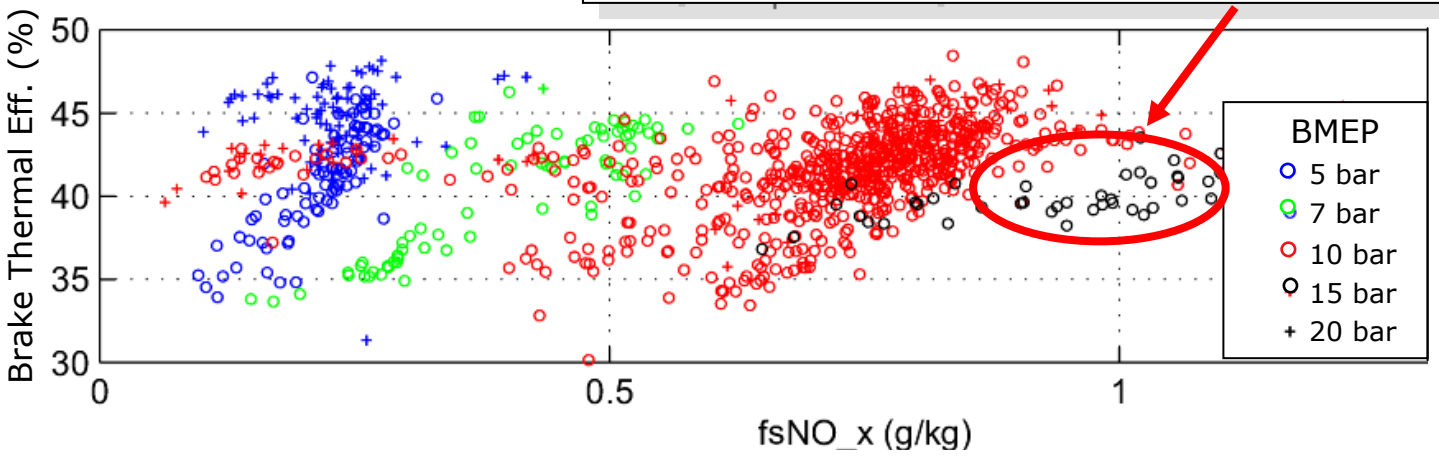
Equivalence Ratio Contours

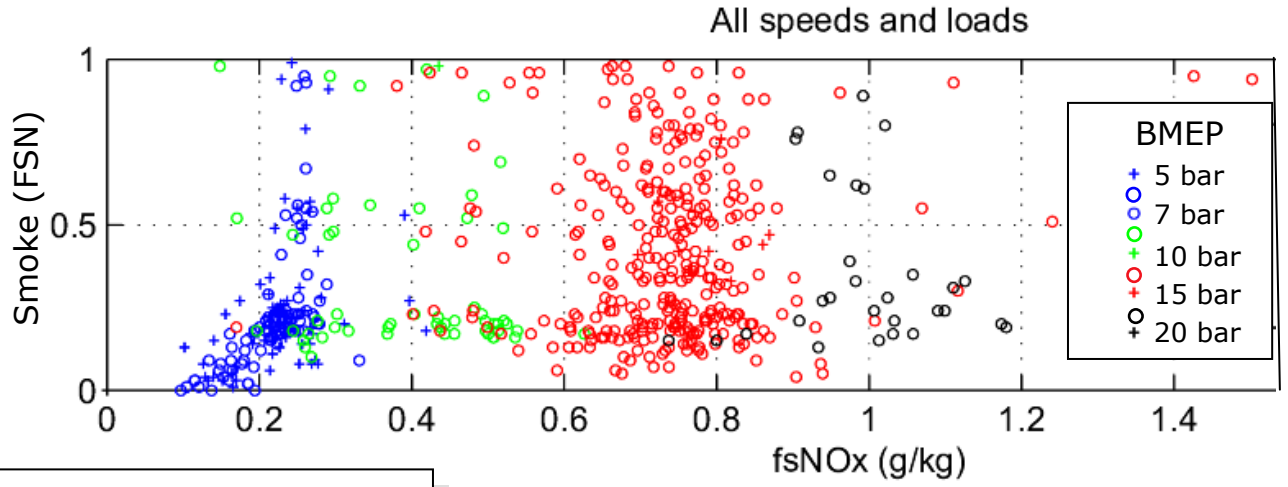


Images Courtesy of Mark Musculus - SNL

Extending the Engine Operation Range of PCCI

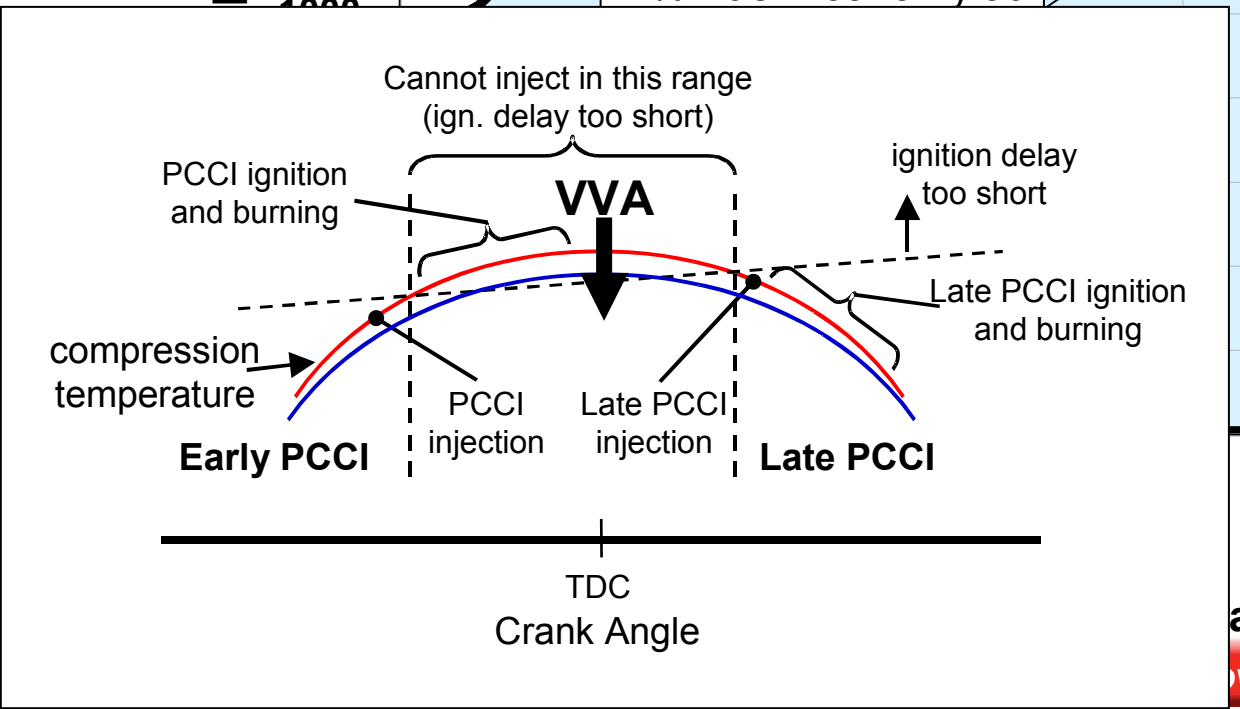
Late PCCI limits fuel economy improvement potential and robustness





Combined Early and Late PCCI

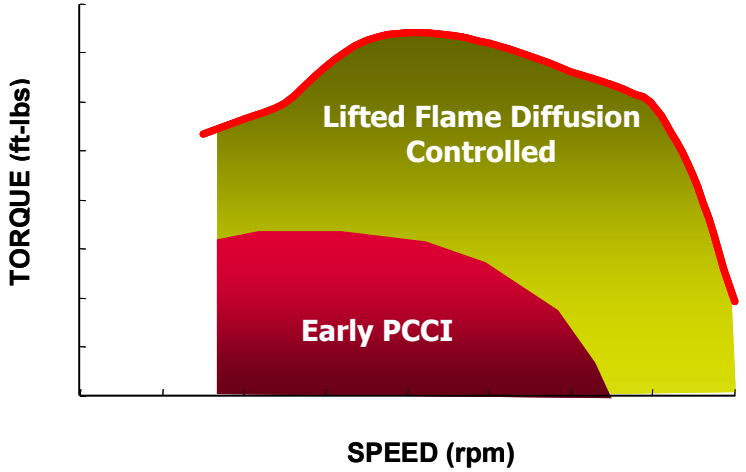
Extending PCCI Combustion with VVA



ation with smoke ≤ 0.5 FSN

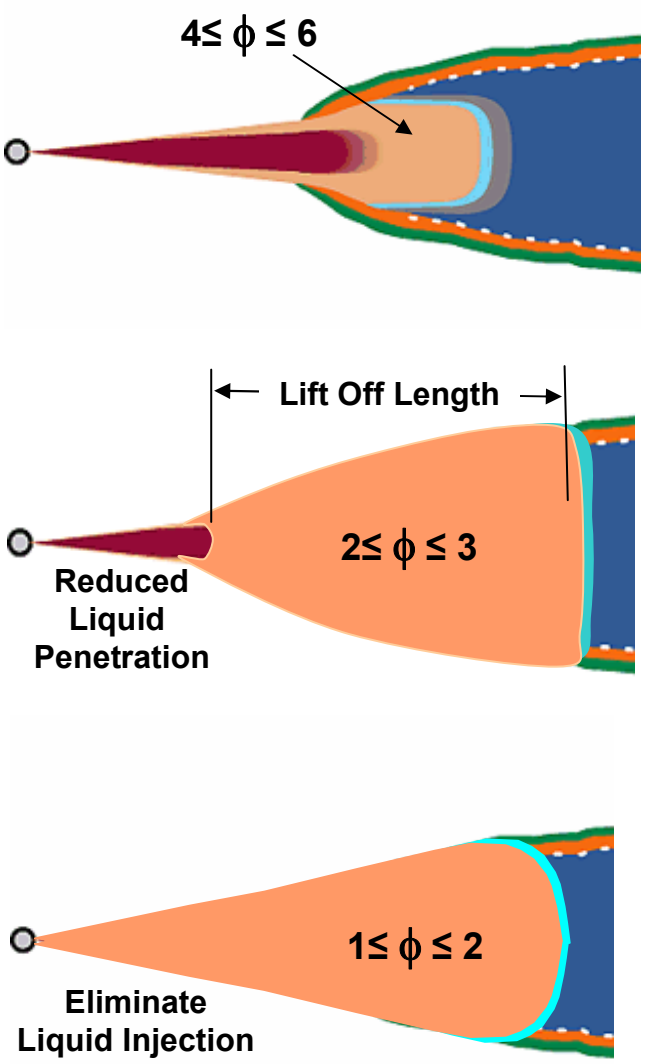
Challenges for Lifted Flame Combustion

- Creating desired intake valve closing conditions
  - A/F, EGR, IMT
- Fuel injection system technology
  - Injection pressure
  - Nozzle configuration
- Fuel injection plume to plume interaction
- Combustion surfaces
  - Difficult to scale to smaller bore engines
- Controls development for transient operation



Creating Lifted Flame Combustion

Reduce Liquid Fuel Penetration and Enhance Fluid Entrainment

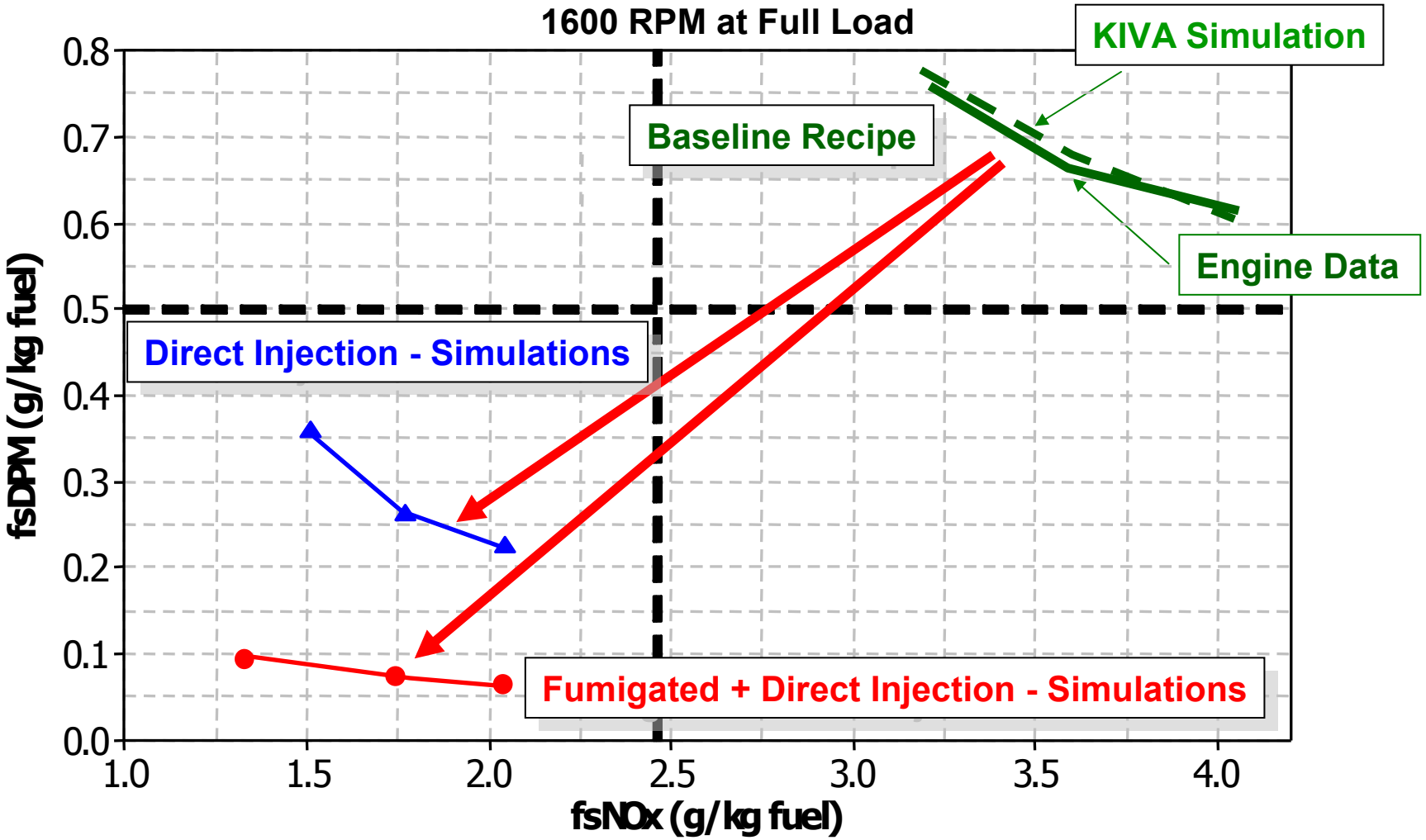


Conventional Diffusion Combustion

Lifted Flame Diffusion Combustion

Advanced Lifted Flame Combustion
(Scales well for smaller bore engines)

Advanced Lifted Flame Combustion



Achieving High Efficiency Combustion with a Wide Portfolio of Fuels

- Wide variety of fuel types
- Engines designed and sold for a global market
- Mixed mode combustion
- Robustness of operation
- Maintain fuel efficiency gains

Virtual and Real Sensor Exploration

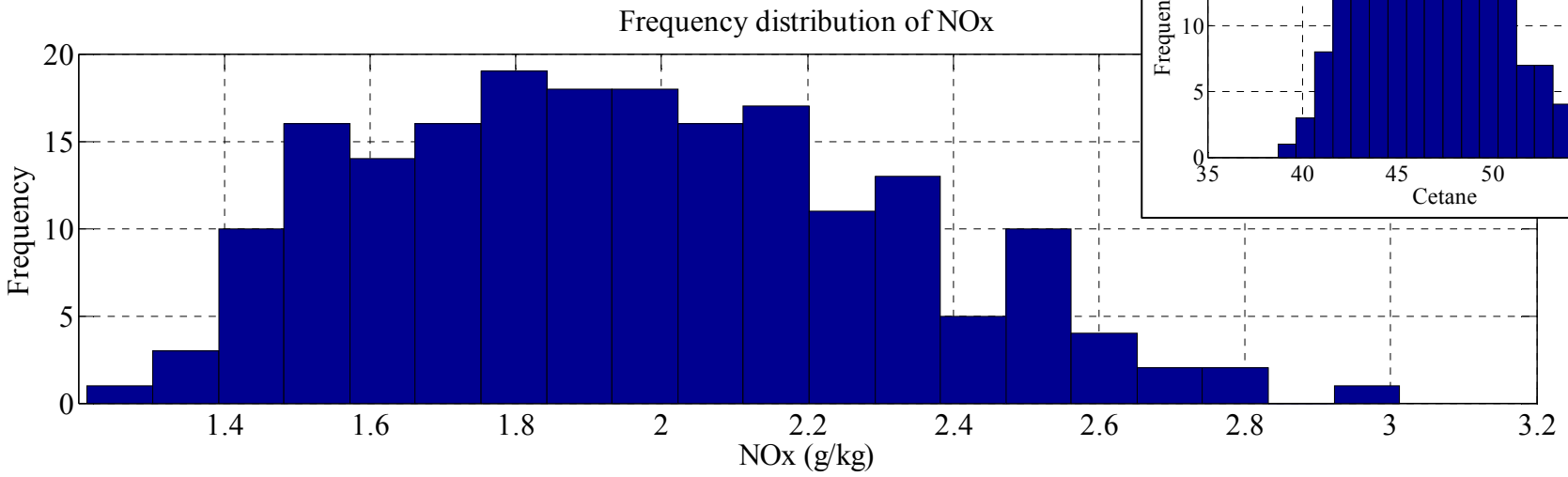
- Exploit fuel properties for performance improvements

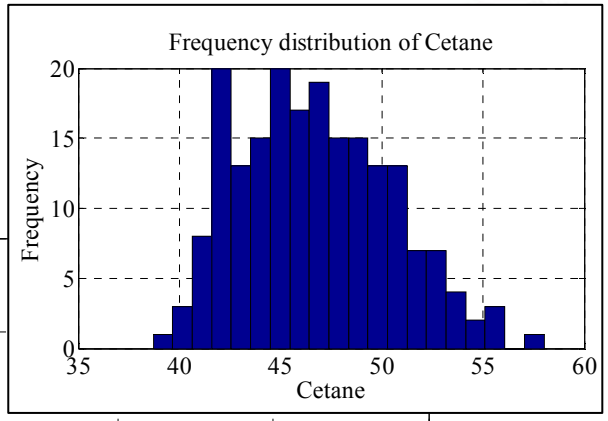
Exploration of Fuel Properties on HECC*

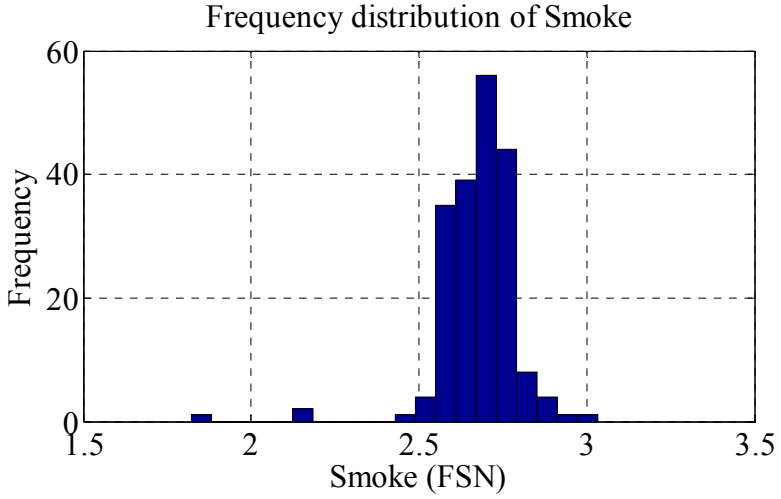
- Use transient engine operation as key data sets for understanding impact of fuel properties on HECC
- Explore the impact of fuel type over a variety of advanced combustion modes
- Characterize the fuel compounds and properties
  - Challenging for heavy fuels
- Explore real and virtual fuel quality sensor technology for engine integration
- Development of kinetics mechanism for analysis
  - CFD analysis – primary way to generalize key combustion knowledge gained from external collaborations

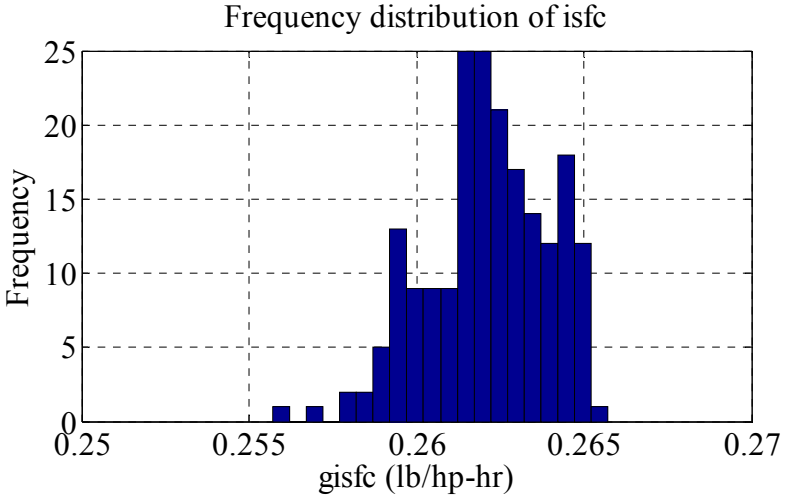
***Partners: ORNL and BP**

PCCI Engine Performance Variation with ULSD

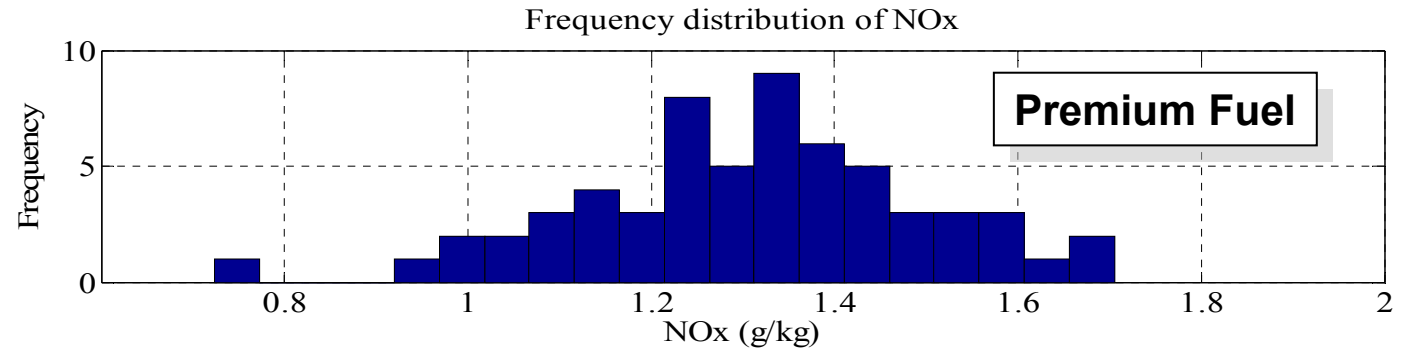


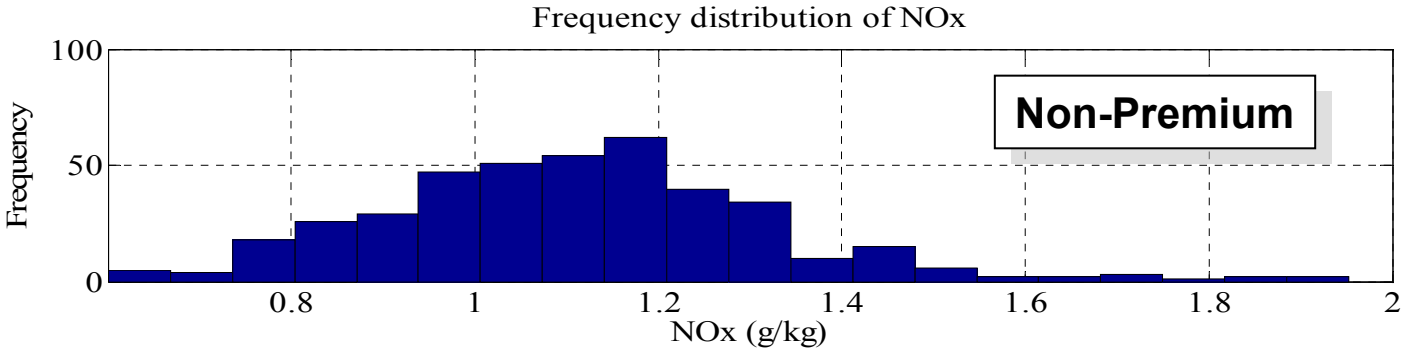


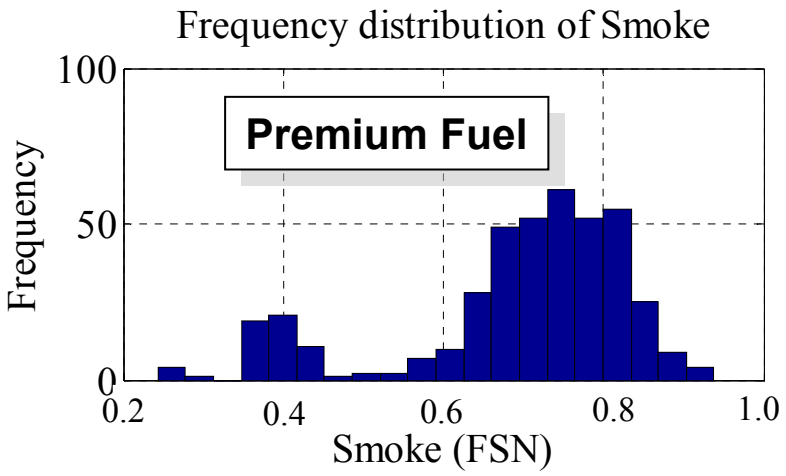


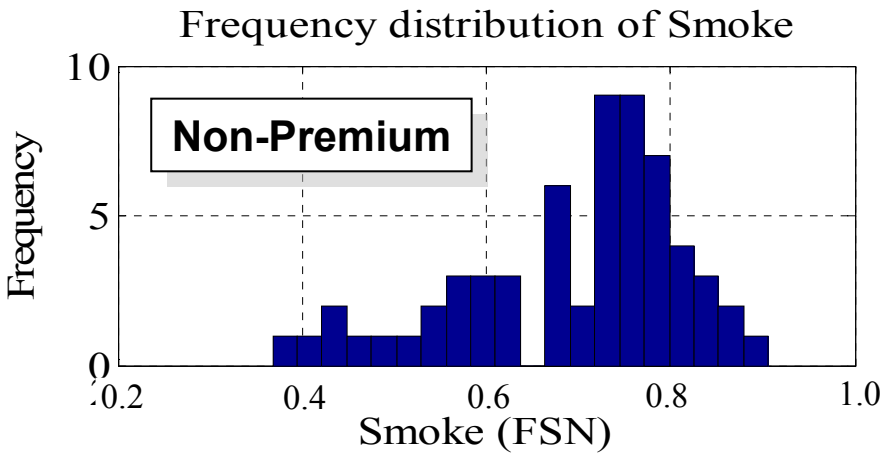


fsNOx, gisfc, smoke, etc = f(engine parameters) + f(fuel properties)


Frequency distribution of NOx
Premium Fuel
Frequency
NOx (g/kg)
0
5
10
0.8
1
1.2
1.4
1.6
1.8
2

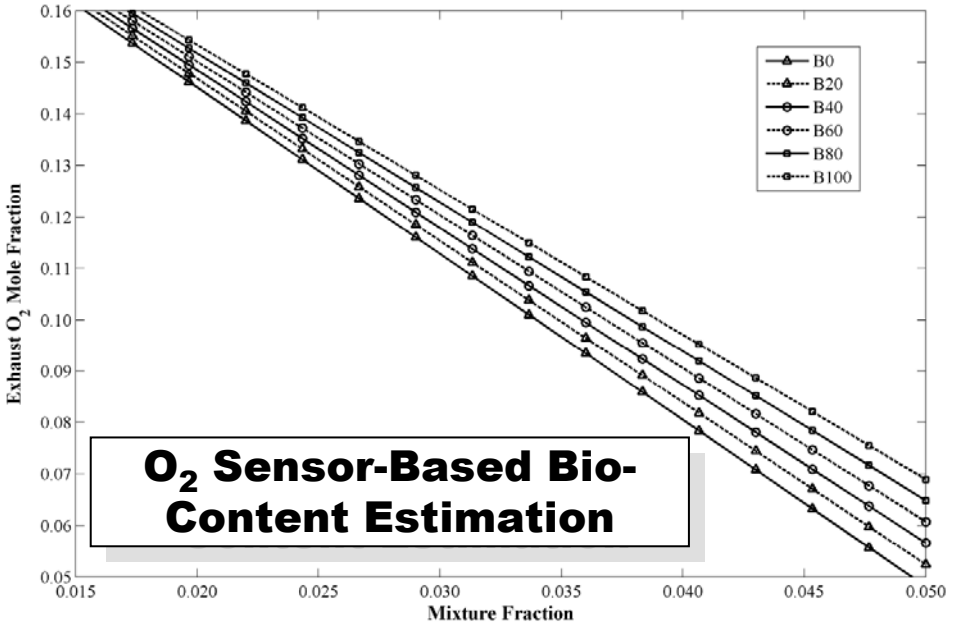

Frequency distribution of NOx
Non-Premium
Frequency
NOx (g/kg)
0
50
100
0.8
1
1.2
1.4
1.6
1.8
2


Frequency distribution of Smoke
Premium Fuel
Frequency
Smoke (FSN)
0
50
100
0.2
0.4
0.6
0.8
1.0


Frequency distribution of Smoke
Non-Premium
Frequency
Smoke (FSN)
0
5
10
0.2
0.4
0.6
0.8
1.0

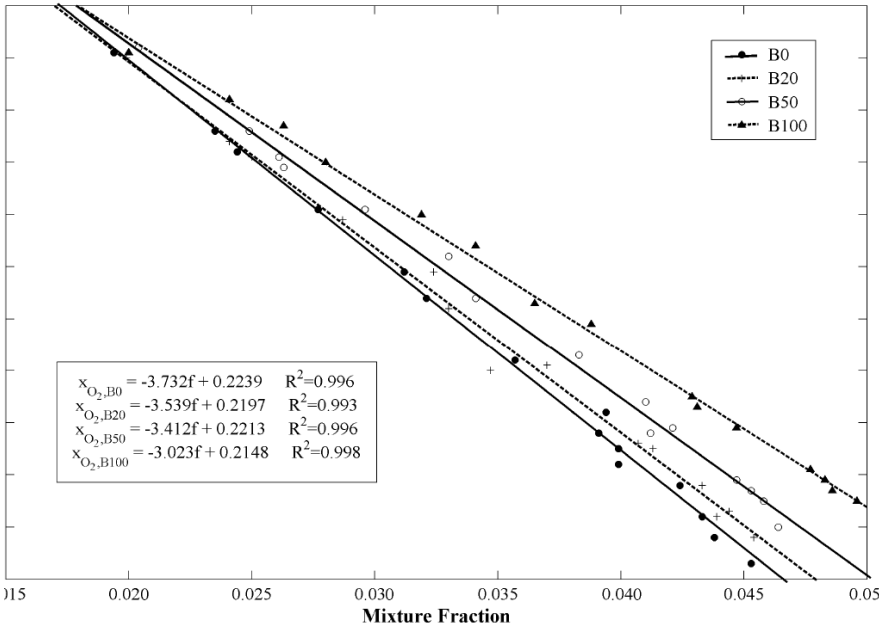
Biofuels Sensing

Virtual Sensor Technology



O_2 Sensor-Based Bio-Content Estimation

Model Prediction



Experimental results

Courtesy: Professor Shaver – Purdue University

Summary

- Mixed mode combustion can achieve a wide range of engine out NOx (≥0.2 g/bhp-hr)
  - Select the right technology for each application
- Development and integration of component technologies are key enablers
- Additional technology exploration needed to achieve greater emission robustness and fuel economy at 0.2 g/bhp-hr engine out NOx
  - Advanced combustion strategies are being explored to promote lifted flame combustion and extended range PCCI combustion
- Virtual and real fuel sensors are enablers for robust performance while maintaining high efficiency as fuel properties variation increases

Variable Swirl – Emissions Robustness