Potential efficiency impacts of low-temperature combustion modes

Paul Miles
Sandia National Laboratories

Combustion Engine Efficiency Colloquium
March 3-4, 2010
Southfield, MI

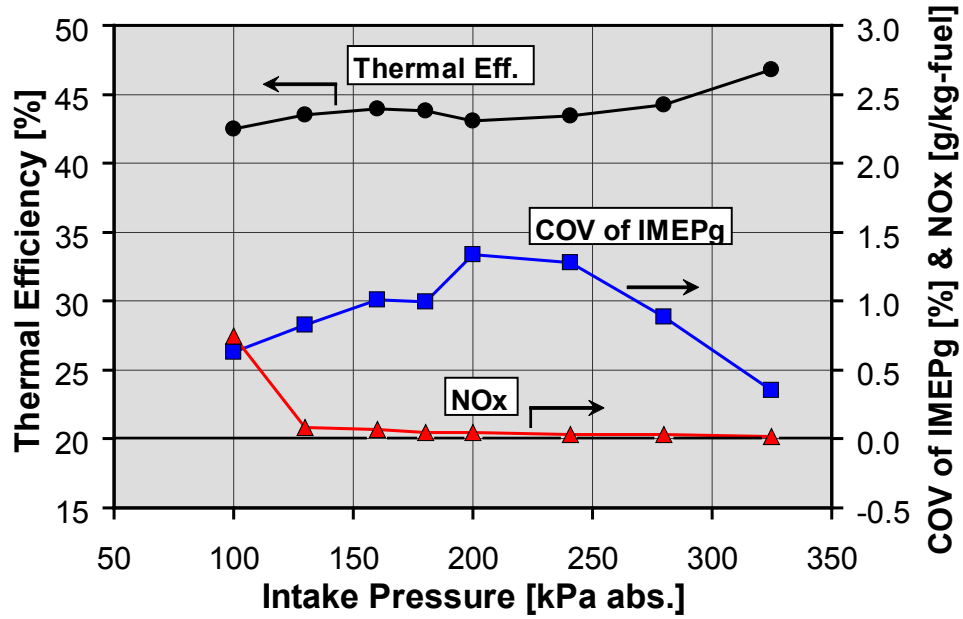
Primary Levers for Increasing Engine Efficiency

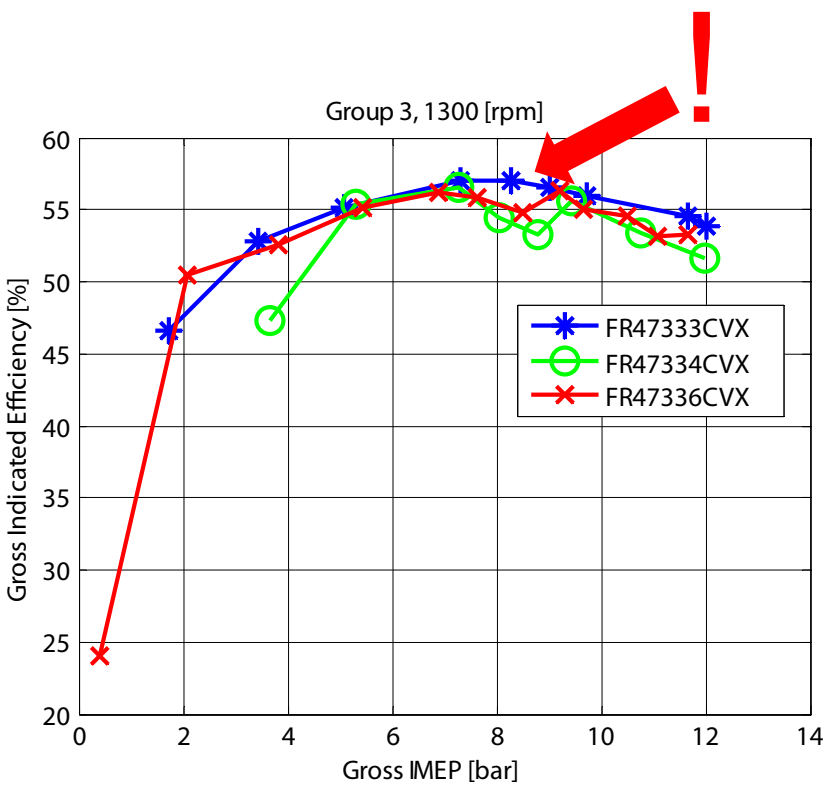
1) **Down-sizing, down-speeding** Reduces relative parasitic losses, friction
2) **Throttling loss reduction** Stratified DI, diesel or gasoline, can enable this.
3) **Light-weighting** Couples with downsizing. Are two-strokes a possibility for some markets?
4) **Thermodynamically advantageous heat release rates** (i.e., more constant volume) Limited by peak cylinder pressure and combustion noise constraints
5) **Advanced thermodynamic cycles (Miller/Atkinson)**.
   Enabled by VVT & turbos, possibly variable compression ratio.
6) **Reduced heat transfer**
7) **Reduction of aftertreatment fuel penalty** (also cost reduction: this will affect market penetration rates)
8) **Alternative fuels**
9) **Hybridization** – links to down-sizing/down-speeding
10) **Waste heat recovery**

Each of these factors either impacts or is affected by combustion

Low-emission combustion does not necessarily result in low thermal efficiency

Indicated thermal efficiencies of 47% (and peak loads greater than 16 bar, T2B2 NOx) have been demonstrated with boosted HCCI using conventional fuels (Dec, DEER2009)

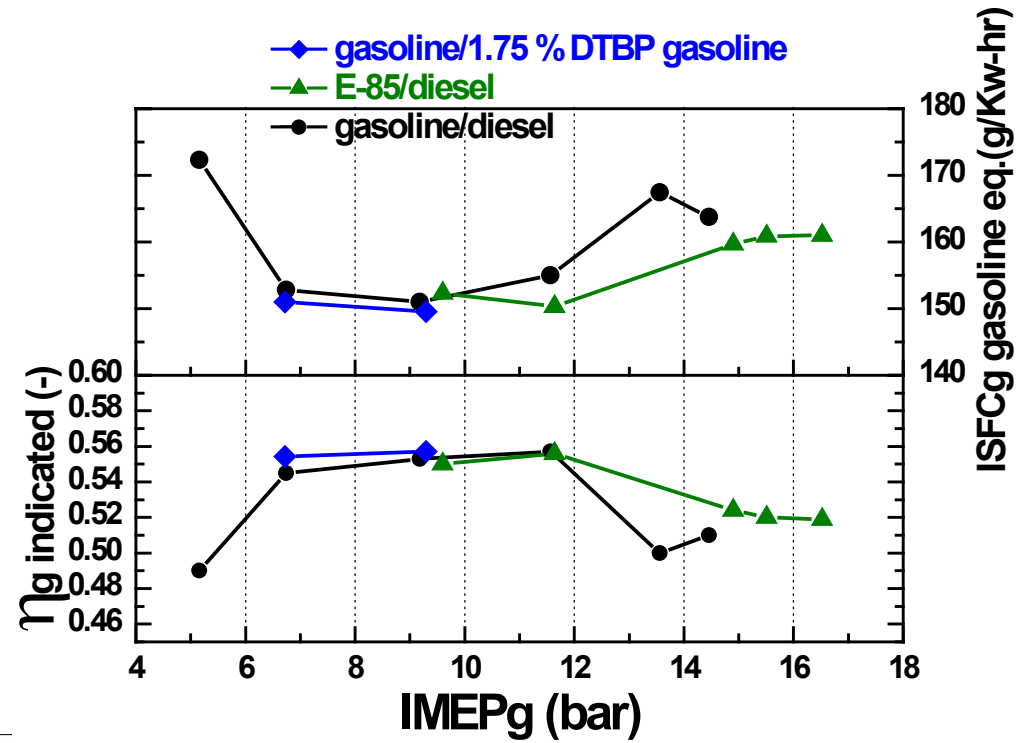


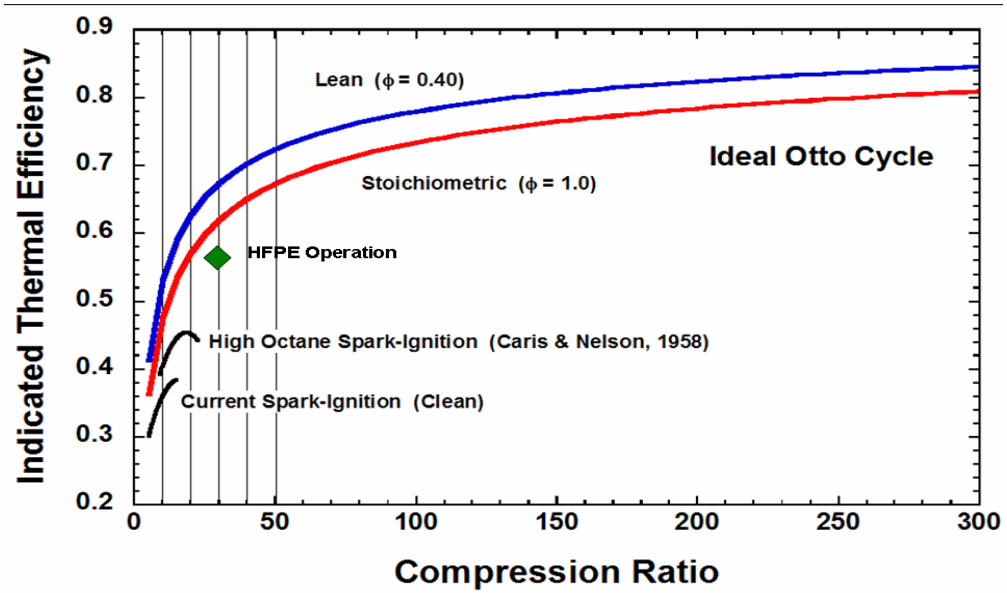


57% peak indicated thermal efficiency has been reported for partially-premixed, compression ignition combustion using gasoline (Johansson, SAE Fall PF&L 2009)

Low-emission combustion does not necessarily result in low thermal efficiency

Dual-fuel studies at the University of Wisconsin have shown indicated efficiencies exceeding 55% (Splitter, AEC Feb. 2010)





HCCI operation in linear, free-piston engines also offers high efficiency potential (Van Blarigan, DOE-VT Peer Review, May 2009)

Factors affecting brake fuel efficiency

$$\eta_b = \eta_m \eta_t \boxed{\eta_c}$$

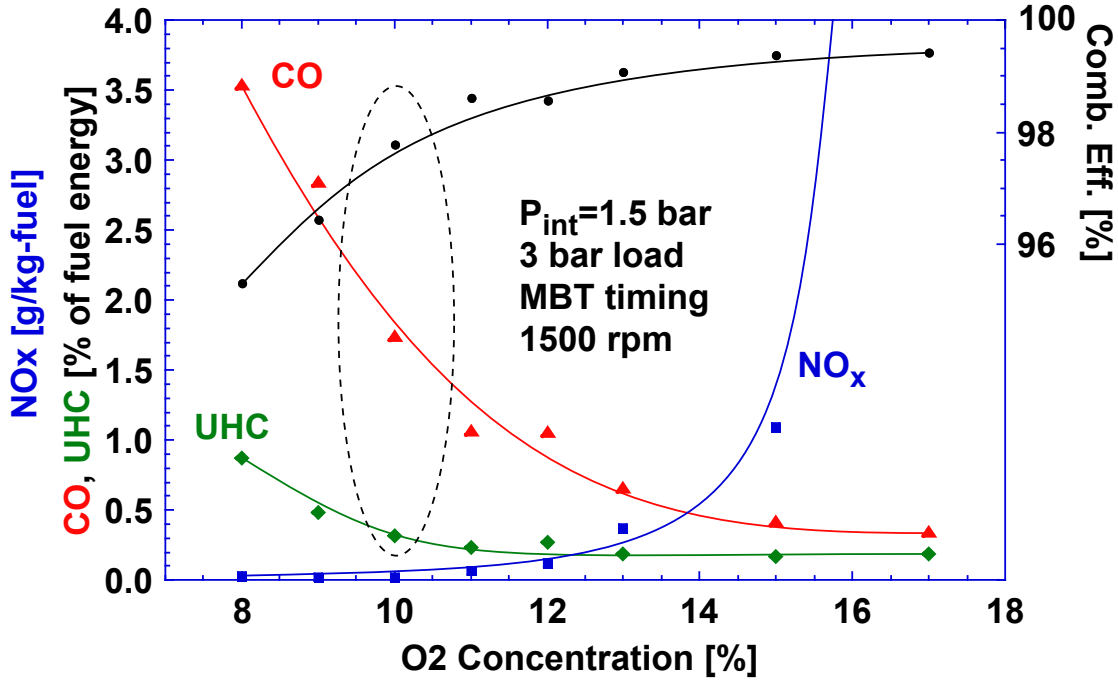
$$\frac{\text{Net chemical energy released}}{m_f Q_{LHV}}$$

- Low η_c manifested by "fuel" in the exhaust gases (CO, UHC, H_2 ...)
- Normally high
  - > 0.98 diesels
  - > 0.95 spark
- Can drop drastically for low-temperature diesel or HCCI

Light-load, low-temperature combustion often results in low combustion efficiency

CO and UHC emissions increase rapidly as dilution levels are increased

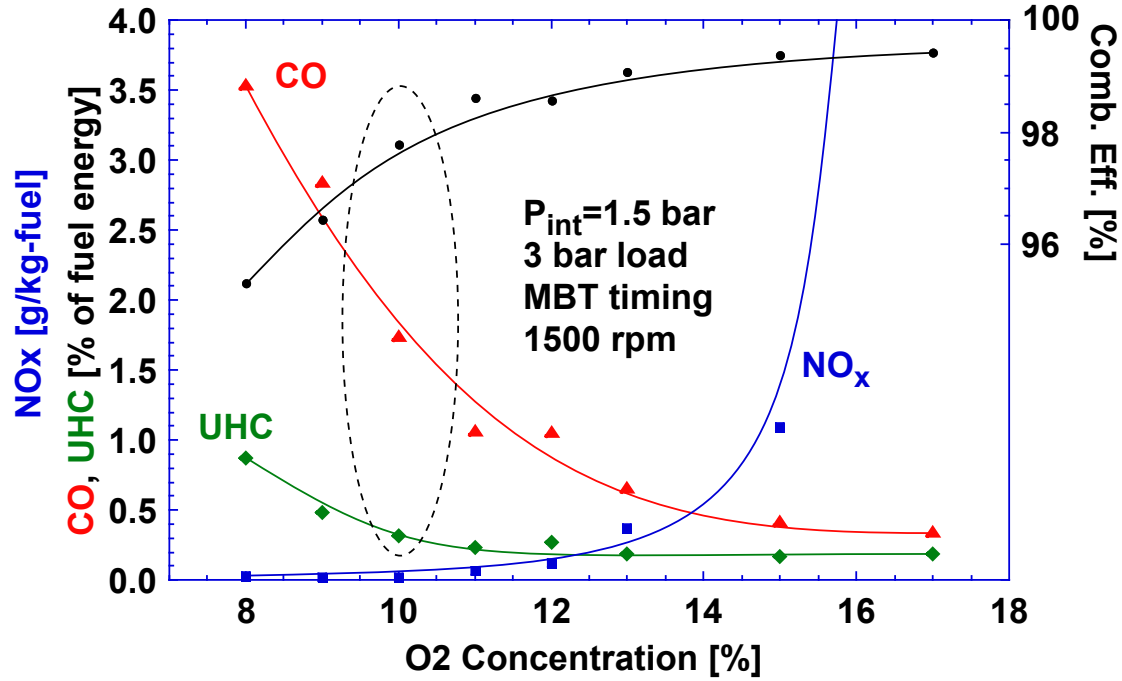
A significant fraction of the fuel energy can be found in these emissions

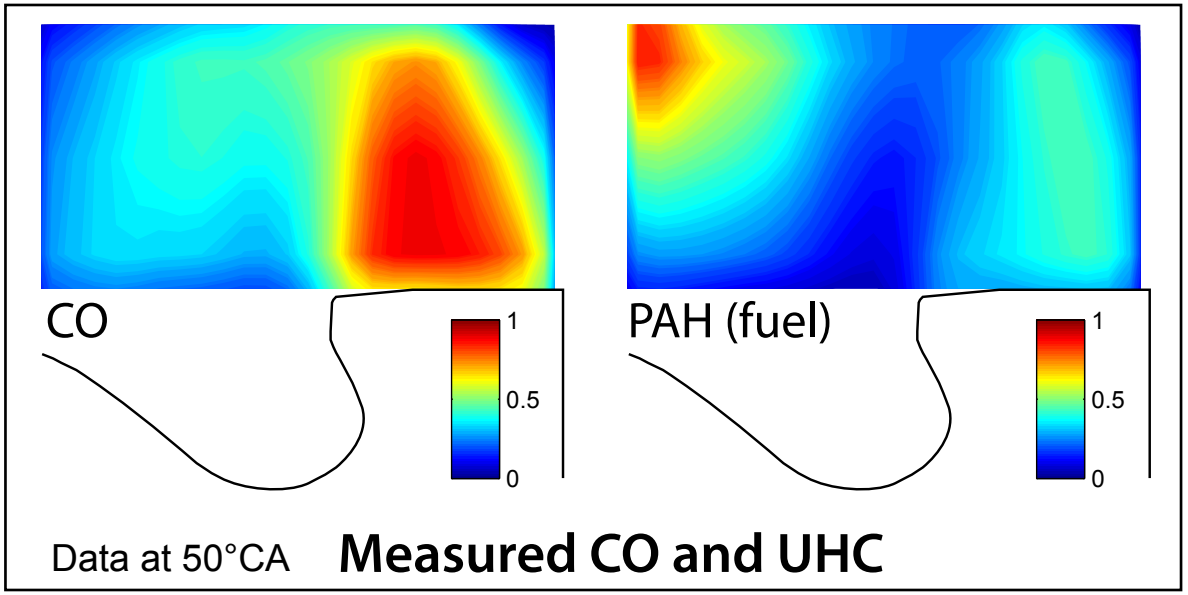


Light-load, low-temperature combustion often results in low combustion efficiency

CO and UHC emissions increase rapidly as dilution levels are increased

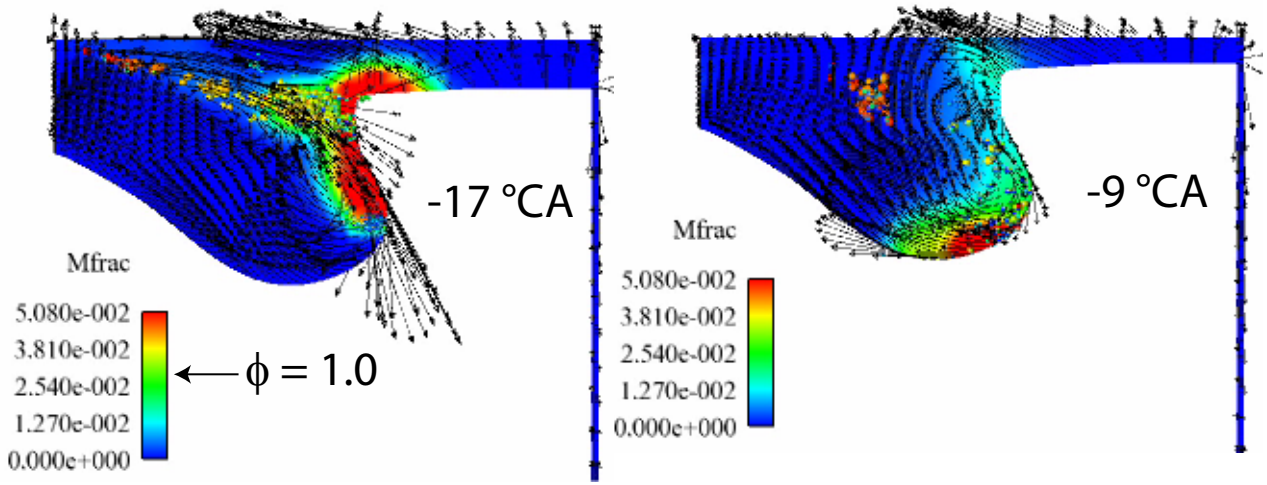
A significant fraction of the fuel energy can be found in these emissions





Most of the CO and UHC is found in the squish volume

Squish volume UHC stems from lean mixtures located near the bowl rim at the time of HTHR



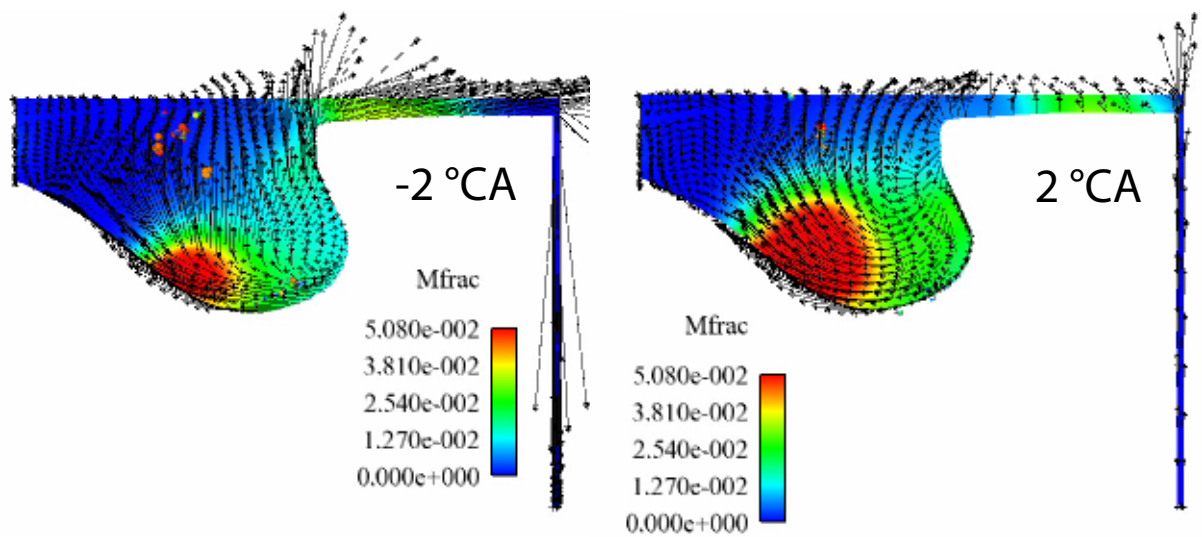
Fuel is injected directly into the squish volume...

...but is forced out by the squish flow

Lean mixture remains near

Gas expansion deep in the bowl forces lean mixture into the squish volume...

...where it further loses heat and oxidized slowly



We need both better understanding and better tools to optimize mixture preparation for best combustion η

Causes of poor mixture distribution are subtle

A better understanding of how optimal mixtures can be prepared, and a more accurate, validated predictive modeling capability, are both needed

Factors affecting brake fuel efficiency

$$\eta_b = \eta_m \boxed{\eta_t} \eta_c$$

$$\frac{\int p\, dV}{\text{Net chemical energy released}}$$

Influenced by:

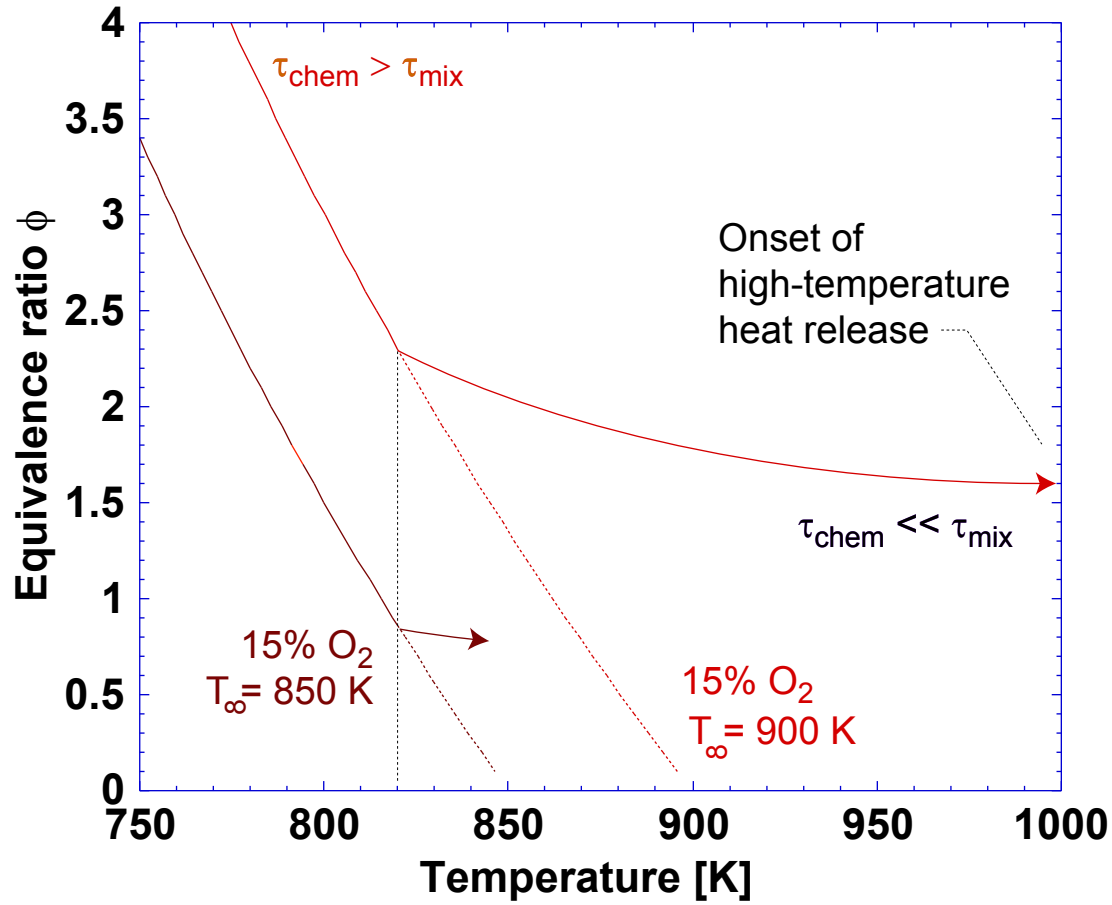
- Compression ratio (Expansion ratio)
- Specific heat ratio
- Combustion phasing and rate of heat release
- Heat transfer losses

Compression ratio reduction is a powerful lever for reducing TDC temperature and increasing mixing

- A 50K decrease in ambient temperature reduces ϕ at the start of low-temperature reaction by over 60%

  Corresponds to:
  - Reduction in T_{in} by 20 K
  - Comp. ratio from 18.7 to 15.6

- The relative magnitudes of chemical and mixing timescales will change with boost and engine speed. Down-sizing and down-speeding can fundamentally alter mixing processes



An predictive modeling capability that accurately captures both turbulent mixing rates and chemical kinetic rates will be useful for optimizing new engines

Compression ratio is a first-order factor impacting the thermodynamic efficiency

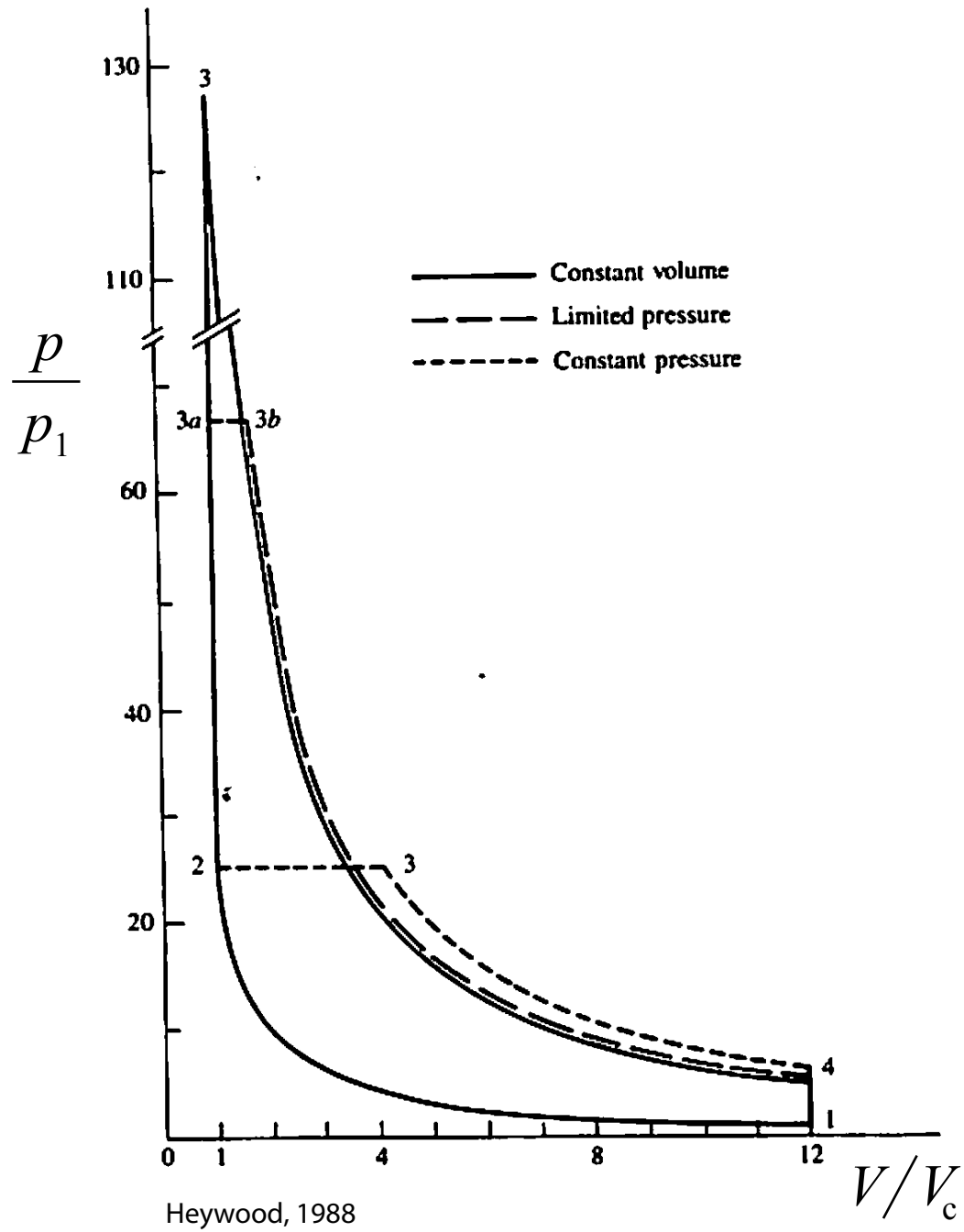
For constant volume combustion:

$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma - 1}}$$

For constant pressure or limited pressure cycles:

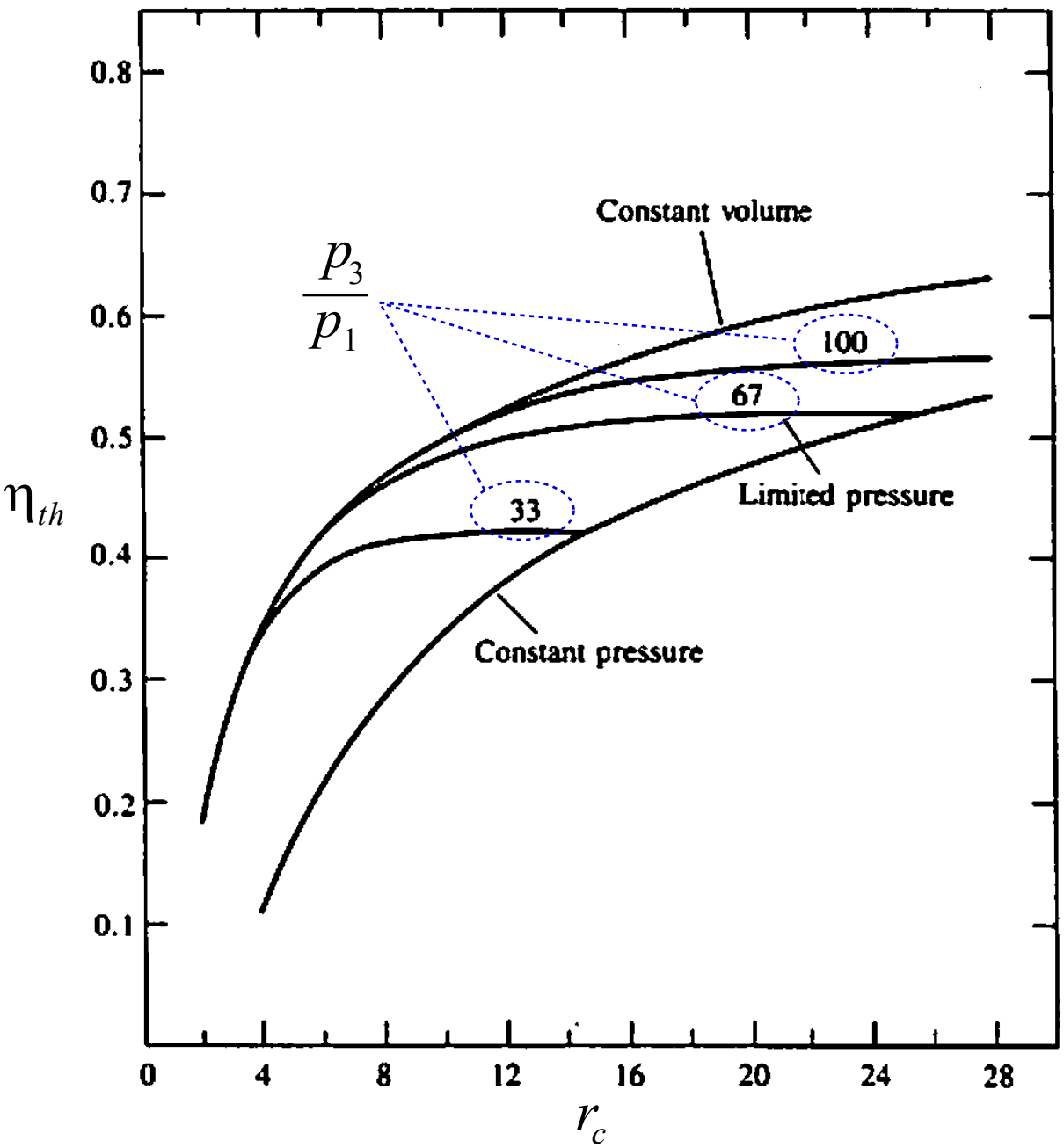
$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma - 1}} \left[\frac{\alpha \beta^{\gamma} - 1}{\alpha \gamma (\beta - 1) + \alpha - 1} \right]$$

$$\alpha = \quad ; \quad \beta = \frac{V_{3b}}{V_{3a}}$$



Heywood, 1988

Impact of constraints on thermal efficiency



For peak cylinder pressures of approximately 200 bar

Intake pressures of 4 bar

$p_3/p_1 \sim 50$

There may be little advantage to $r_c >\sim 15$

(Note: For a given p_3, the constant pressure cycle has the highest efficiency)

We need to consider all of the system constraints

What about the specific heat ratio? (another first order parameter)

$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma - 1}}$$

- Physics gets lost in the thermodynamic derivation
- Expect that lower temperatures generally provide a higher specific heat ratio...and greater work extraction per unit of volume expansion

  Seems to correlate with data
- But low temperatures mean higher EGR rates...lowering γ
- ...and mass flows also increase

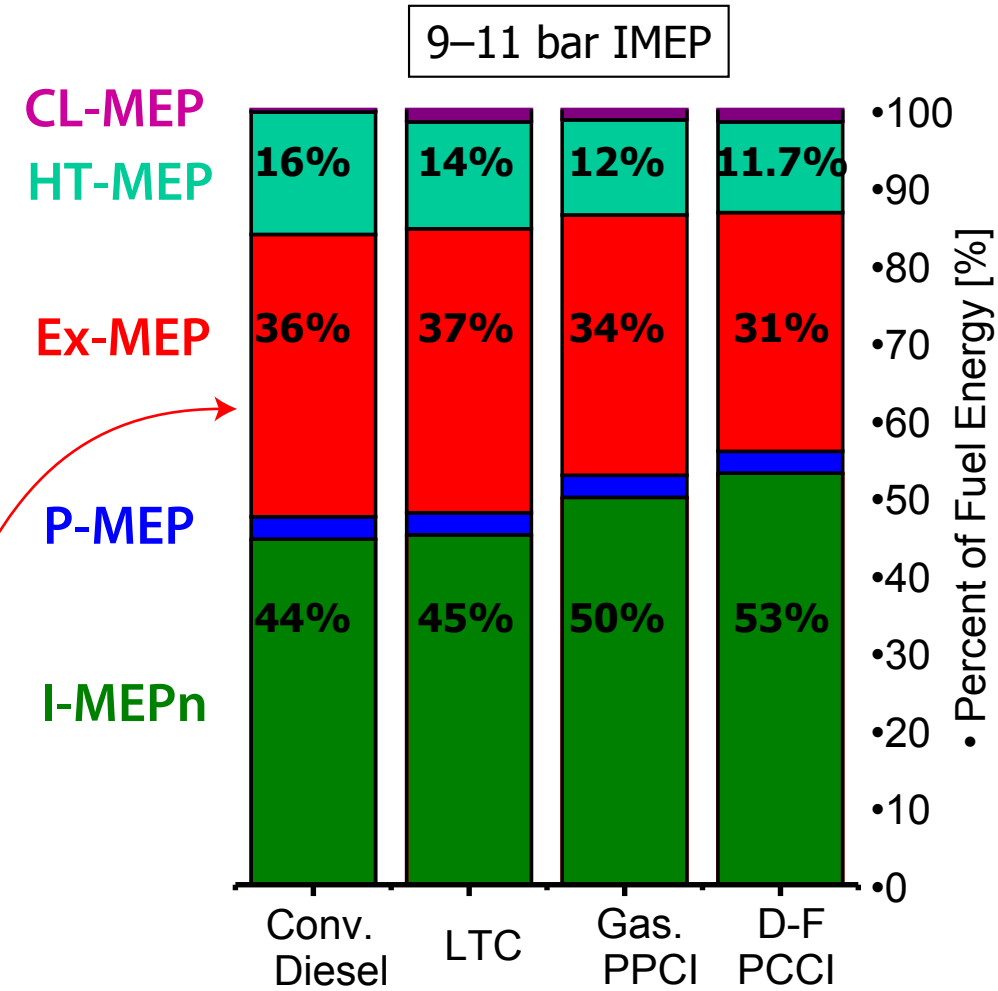


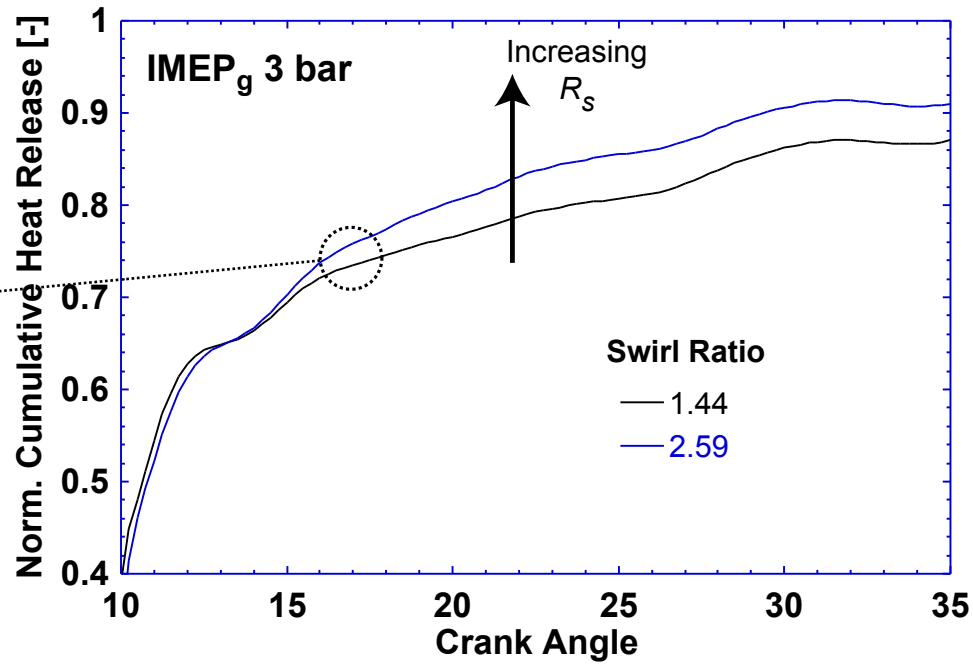
Figure from Foster, SAE Fall PF&L 2009

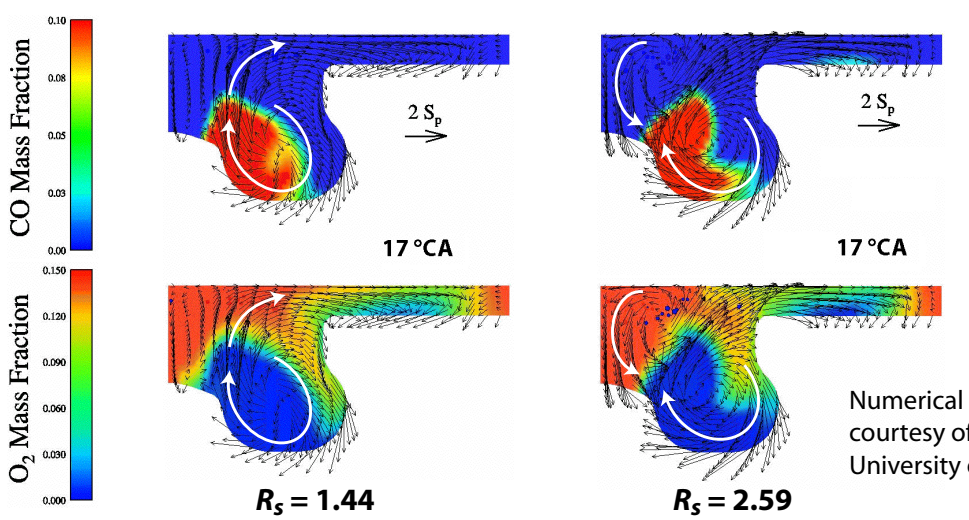
A careful analysis and mental framework characterizing the impact of all of these factors would facilitate understanding and design optimization

Mixing-controlled low-temperature combustion modes often suffer from retarded heat release

Increased swirl increases late-cycle mixing rates...

...though it also likely increases heat losses





Numerical simulations courtesy of RD Reitz, University of Wisconsin

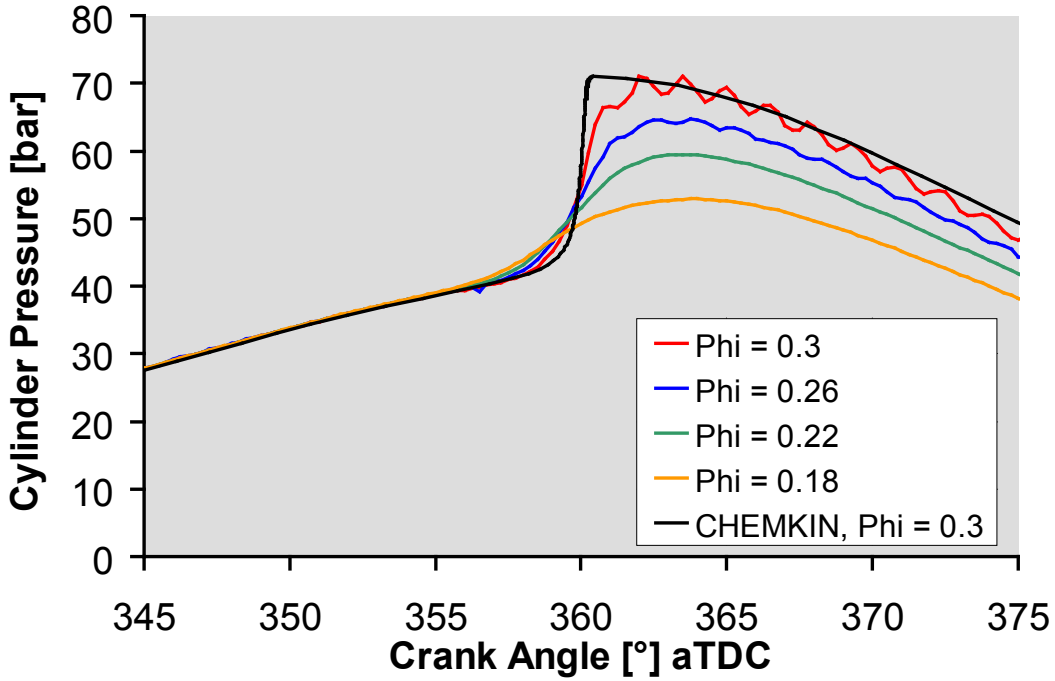
Bulk structures transport unburned fuel and air to a common interface

The ability to accurately predict bulk flow structure formation and their impact on on late-cycle oxidation processes will be important to the optimization of these engines

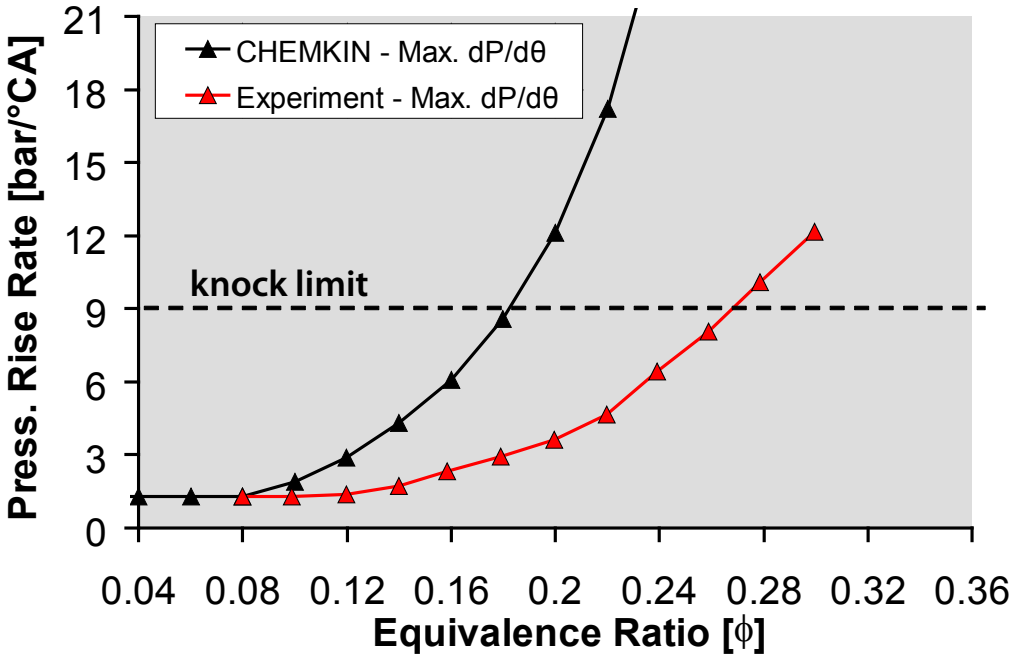
e.g. soot oxidation in a heavy duty engine

In HCCI combustion heat release rates can be too rapid

- Overly rapid heat release often limits the achievable load for HCCI operation
- Both thermal stratification and mixture (ϕ) stratification can help reduce peak pressure rise rates

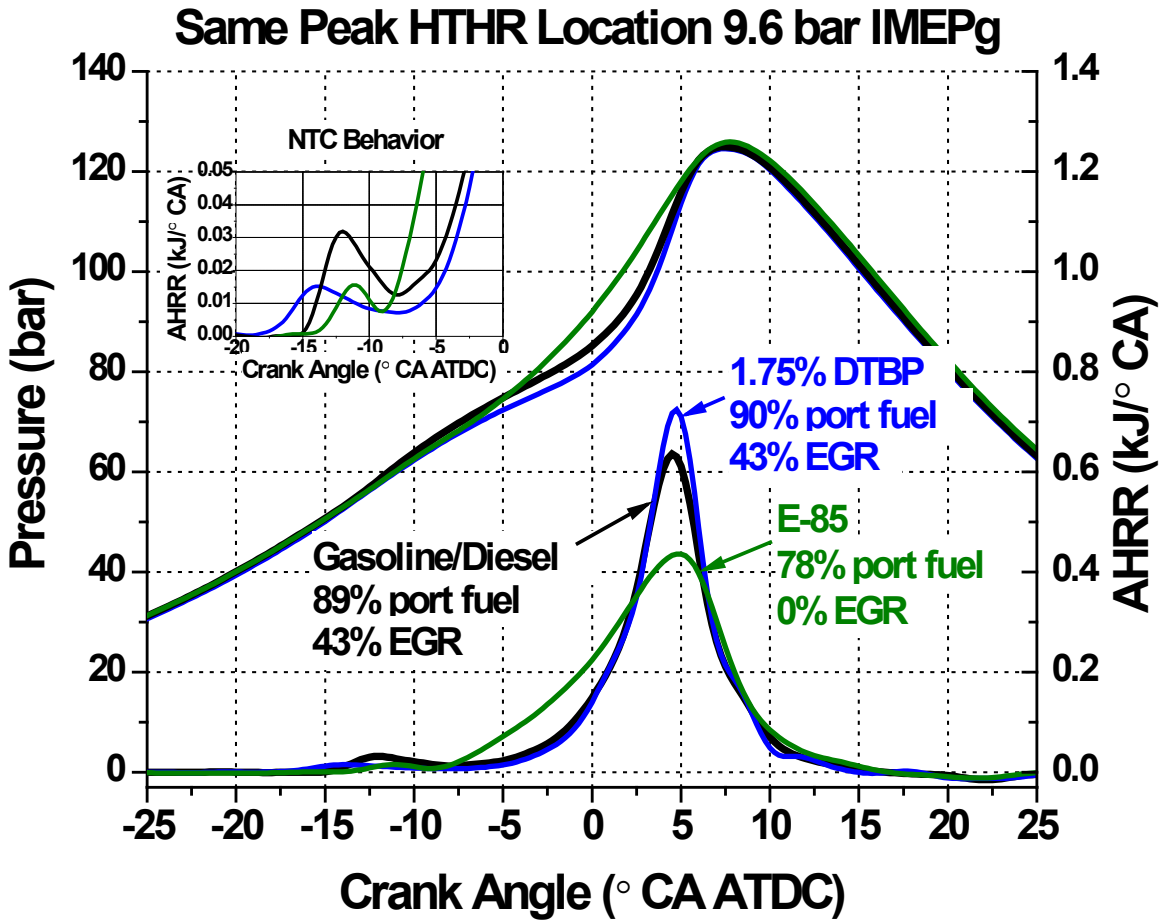


A better understanding of how stratification can best be achieved, and an accurate, validated predictive modeling capability of the ignition and combustion processes for multiple fuels is needed



Fuel reactivity stratification offers significant potential for taming peak heat release rates

Good results have been obtained with both reactivity enhancement and reactivity reduction



Splitter, AEC Feb. 2010

Can we model and correctly predict this behavior?

Reduced heat transfer also appears to be a dominant factor related to higher efficiency

Woschni:

$$h_c \propto B * p^{0.8} * T^{-0.55} * w^{0.8}$$

- Higher pressures will cause greater heat losses
- High EGR rates will cause additional losses through radiative transfer from CO_2 and H_2O
- Reduced radiative transfer from soot will help

Data indicate that overall heat transfer is reduced

Heat transfer is not fully determined by "static" thermodynamic properties (T, p)

- w is influenced by down-speeding
- Flow structure manipulation may also provide a benefit

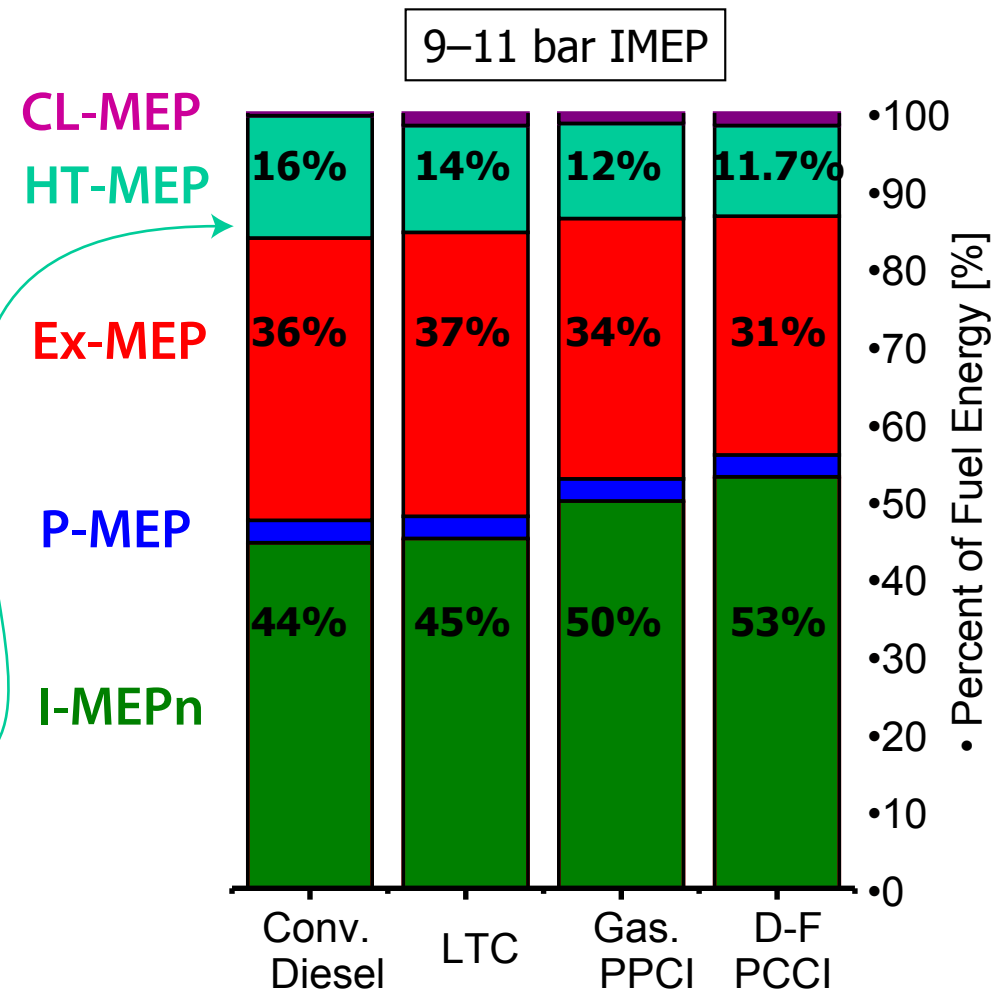


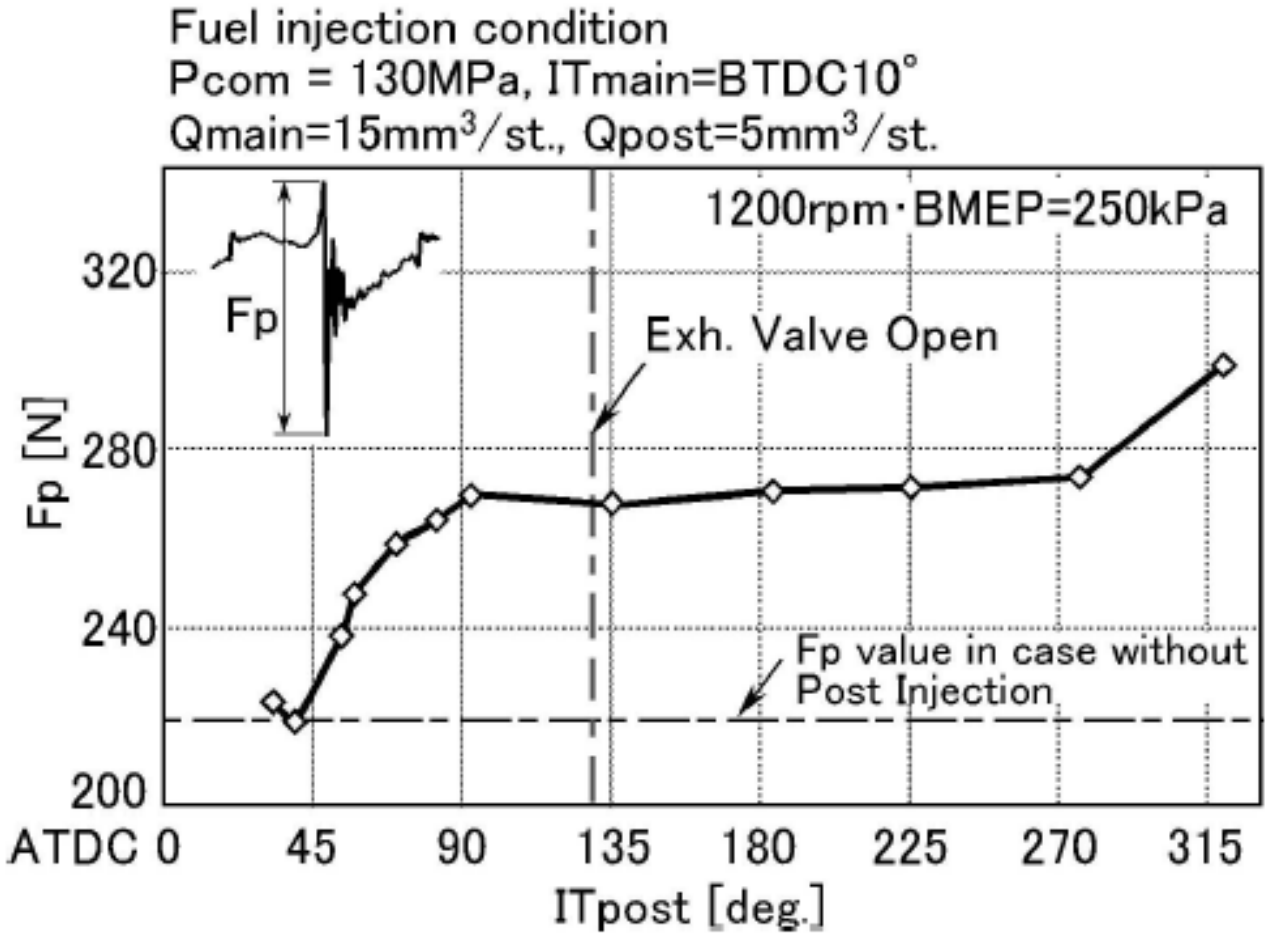
Figure from Foster, SAE Fall PF&L 2009

Factors affecting brake fuel efficiency

$$\eta_b = \boxed{\eta_m}\,\eta_t\,\eta_c$$

- Pumping work
  - Direct injection, stratified
- Friction
  - Downspeeding (τ_{comb} vs. τ_{engine} heat transfer)
  - Downsizing (wall effects, boost)
  - Materials
  - Lubricants (post-injection)
  - Additives
- Accessories

Wall wetting impacts piston friction forces, not just oil sump levels



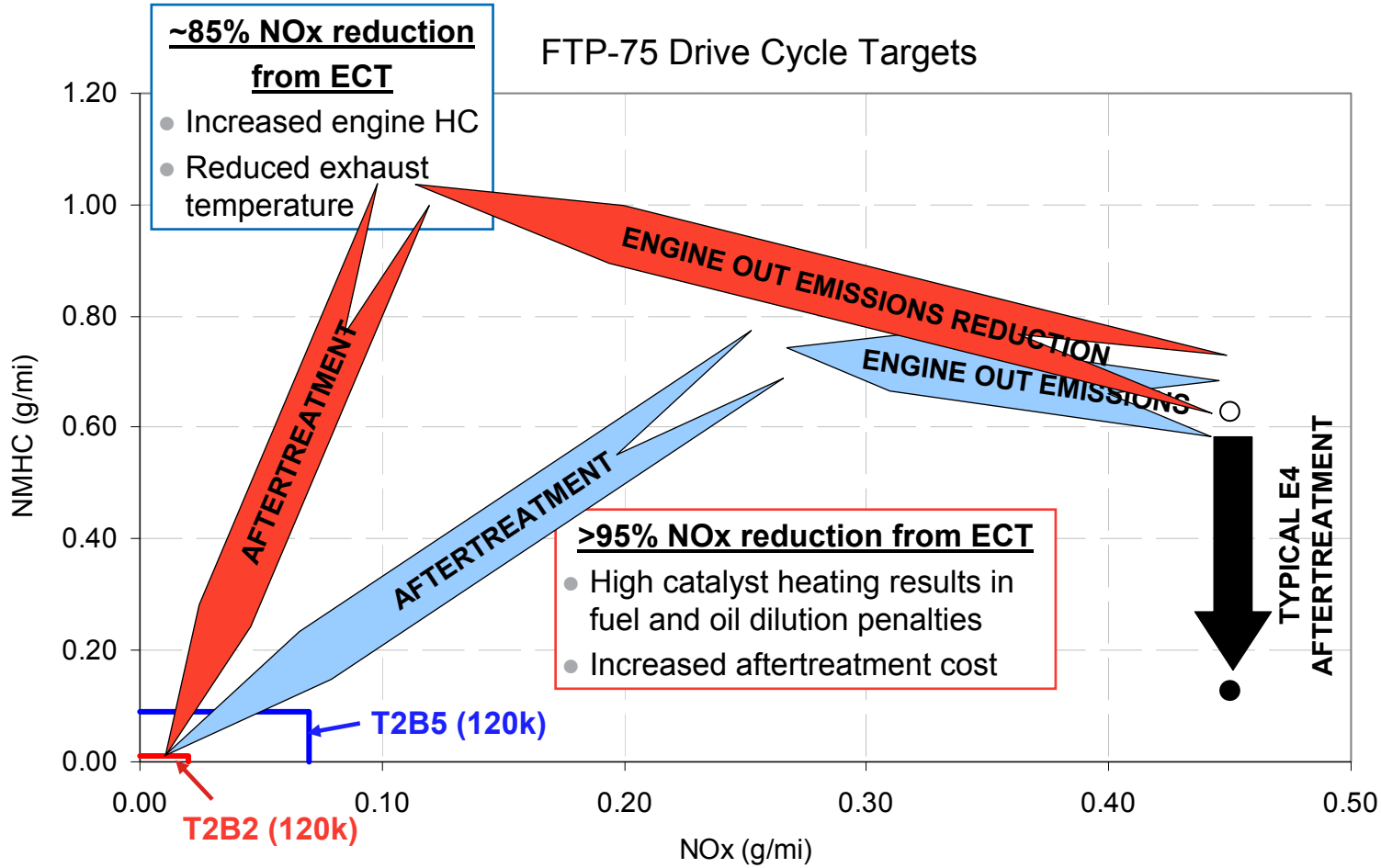
Oinuma, Takuma, Koyano and Takiguchi, SAE Paper no. 2005-01-2166.

As post injection timings are retarded, wall friction increases as the wall wetting worsens

Reduction of aftertreatment fuel penalty

One viewpoint is that low-temperature combustion techniques are essential to meeting T2B5 and T2B2 emissions standards in a cost- and fuel-efficient manner

SULEV Diesel challenge

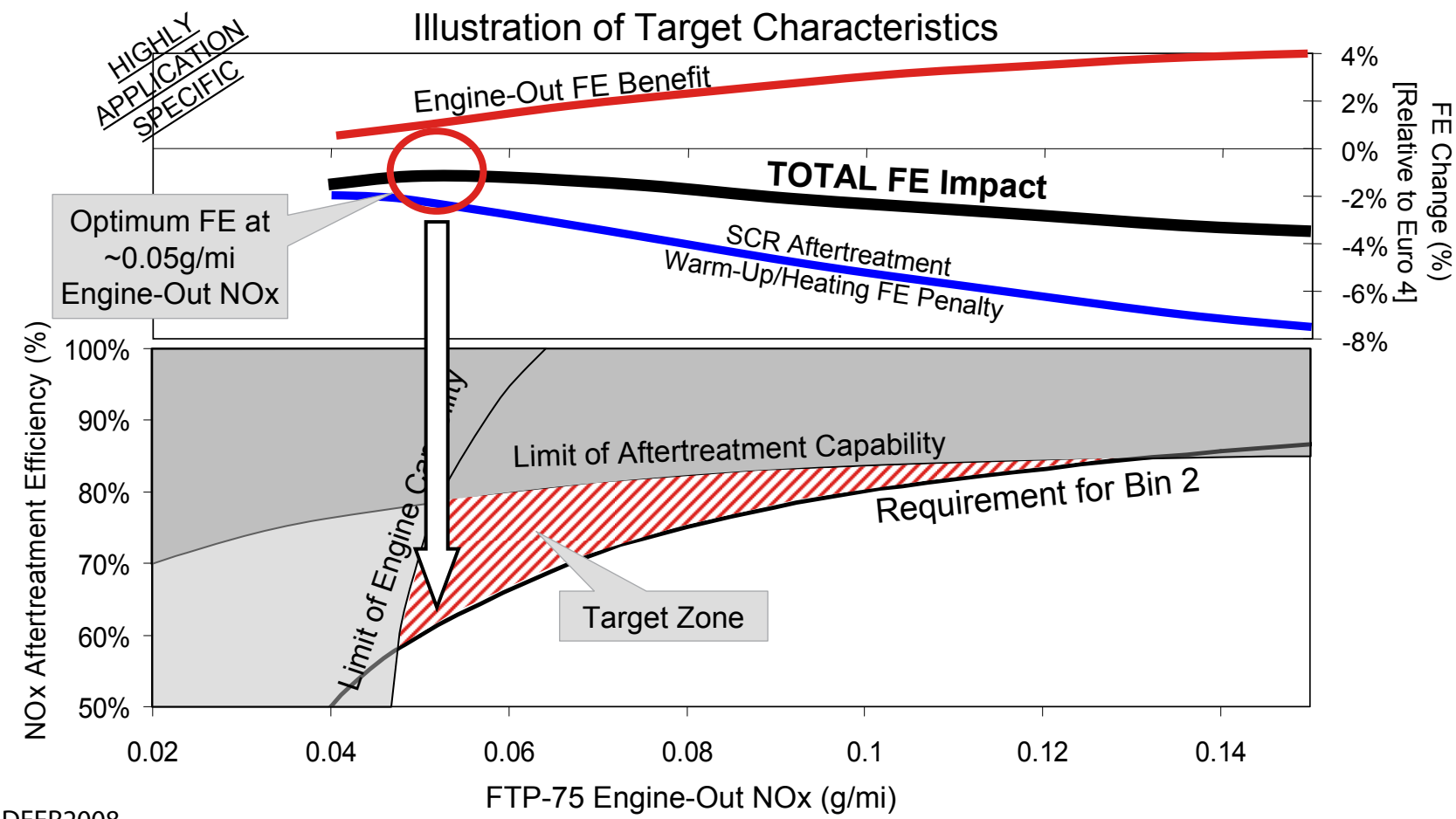


Source: Ricardo, DEER2009

Reduction of aftertreatment fuel penalty

These analyses indicate that best "system" fuel economy occurs when engine-out emissions are minimized, despite increased engine fuel consumption

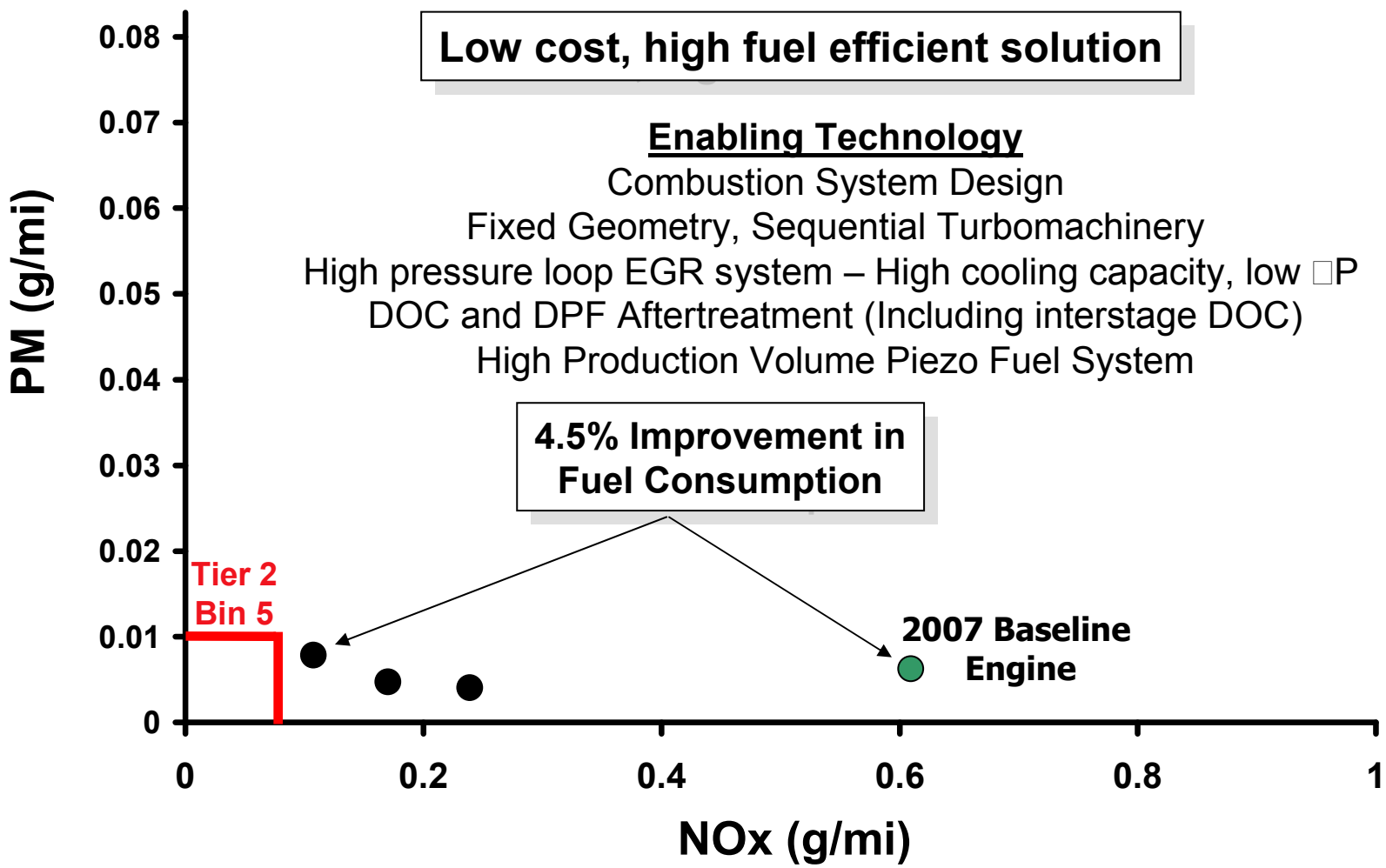
Research is now examining the optimum engine and aftertreatment balance for best fuel economy at T2B2



Source: Ricardo, DEER2008

Reduction of aftertreatment fuel penalty

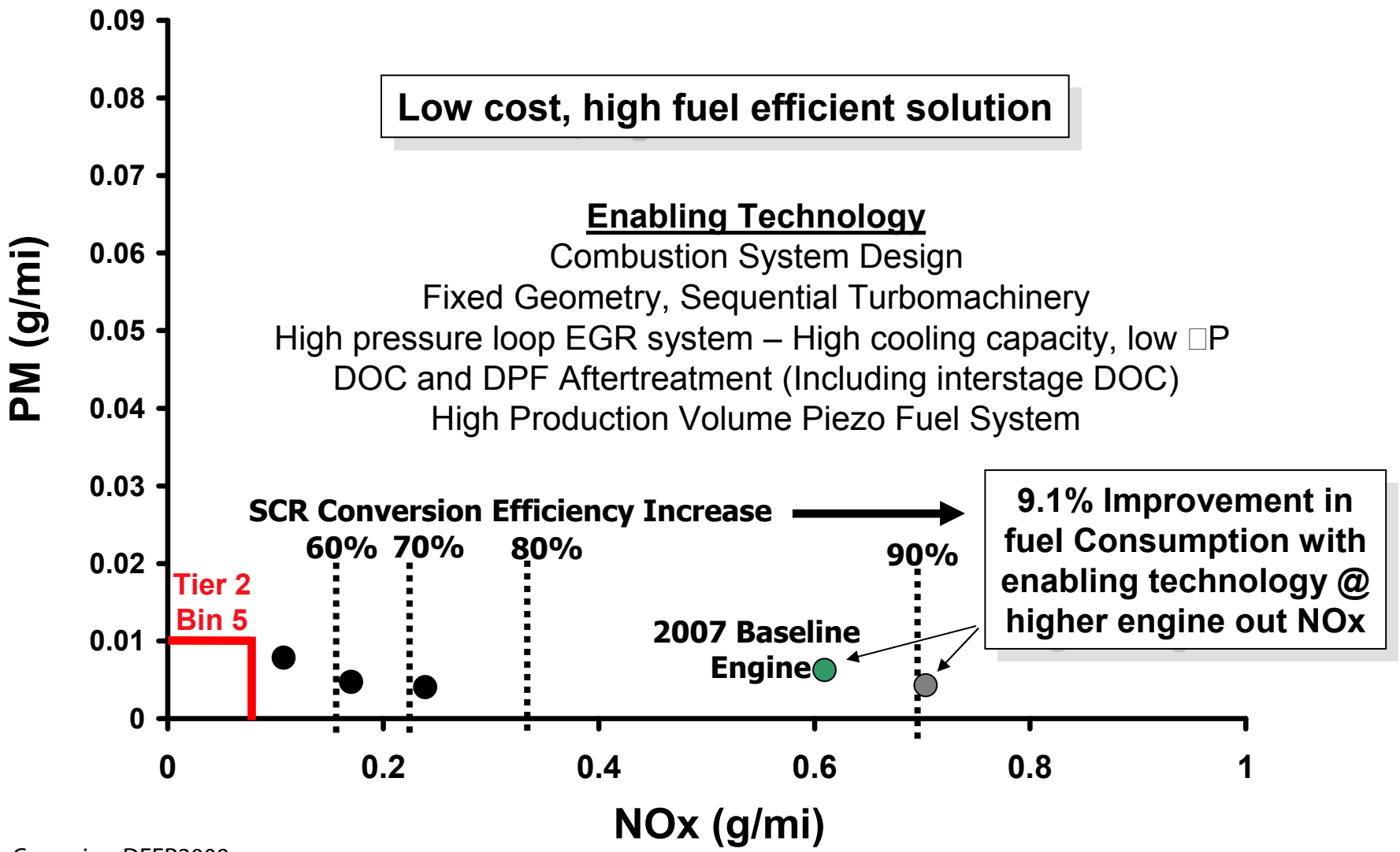
Others find that careful combustion/air-handling/FIE optimization can lead to improved efficiency and lower emissions...



Source: Cummins, DEER2009

Reduction of aftertreatment fuel penalty

...but that an increase in NOx aftertreatment efficiency would enable a more efficient solution



Source: Cummins, DEER2009

Summary

- Combustion impacts all of the various levers we can use to increase fuel efficiency
- Combustion either directly or indirectly impacts all of the efficiency components impacting BTE
- There is a need for a true systems level approach to the efficiency problem:

  Combustion and aftertreatment and air handling

  Part of the systems approach is a need for clear communication of boundary conditions and constraints: Engine load speed map? Max cylinder pressure? Exhaust gas temperature and composition?

  Is there room for a coordinating body or committee?
- Sacrificing engine efficiency for criteria emissions is unacceptable and is not necessarily required. We have made significant progress understanding sources of inefficiency in LTC, but considerable work needs to be done to understand how to best eliminate them

Program elements

A program aimed at increasing engine efficiency will have two essential components:

1) Development of a truly predictive modeling capability on multiple levels

   - Detailed multi-dimensional simulations
   - Low-order models for system optimization

2) Development of a framework for understanding important thermodynamic trade-offs, on a system and on a component level

The designer needs guidance!