Effects of Fuel-type and Engine Speed on Required Intake Temperature and Completeness of Combustion in an HCCI Engine

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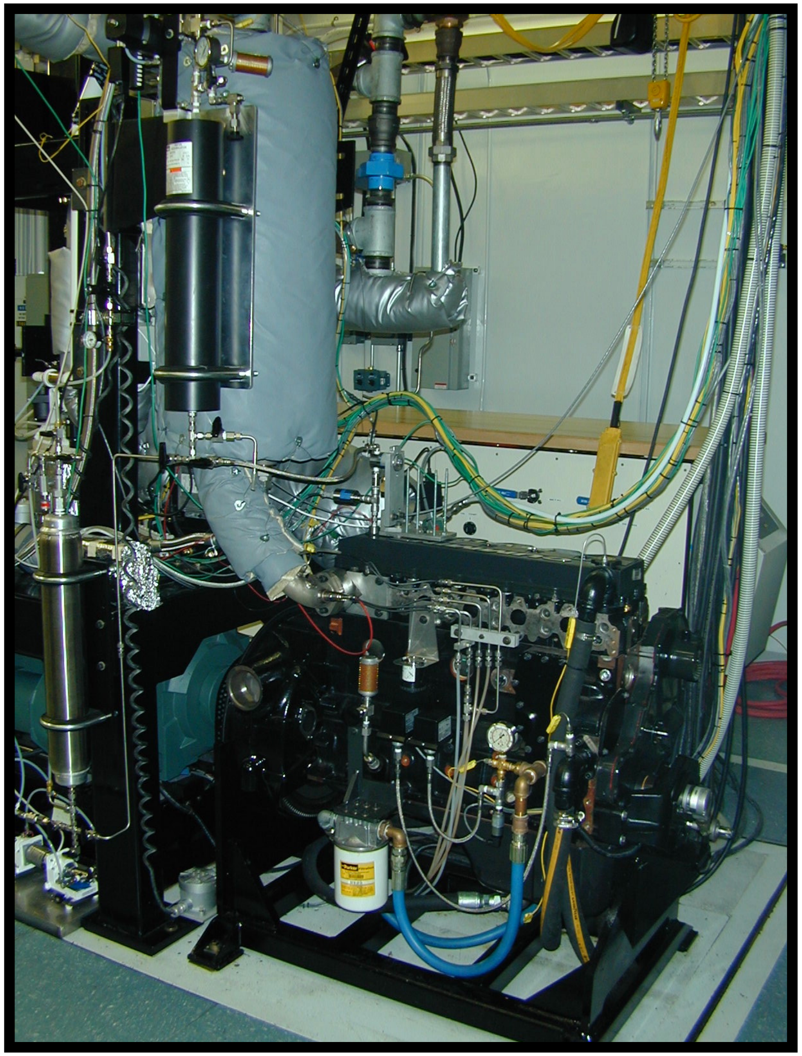
Introduction

- HCCI operation has the potential to provide good fuel economy with low NO_x/ PM, both for gasoline and diesel engines.
- In the near term, HCCI will most likely be implemented only over part of the operating range, at least for automotive applications.
- Combustion phasing, for a given fueling rate, is generally controlled by the temperature at the start of compression (unless VCR or stratified charge).
- <u>Need to understand how the required intake temperature changes with fuel-type and engine speed.</u>
- Combustion efficiency is related to combustion temperatures, and deteriorates below a certain fueling rate.
- <u>Need to understand how this fueling rate changes with fuel-type, engine speed and intake temperature.</u>

Engine and Operating Conditions

HCCI All-Metal Engine

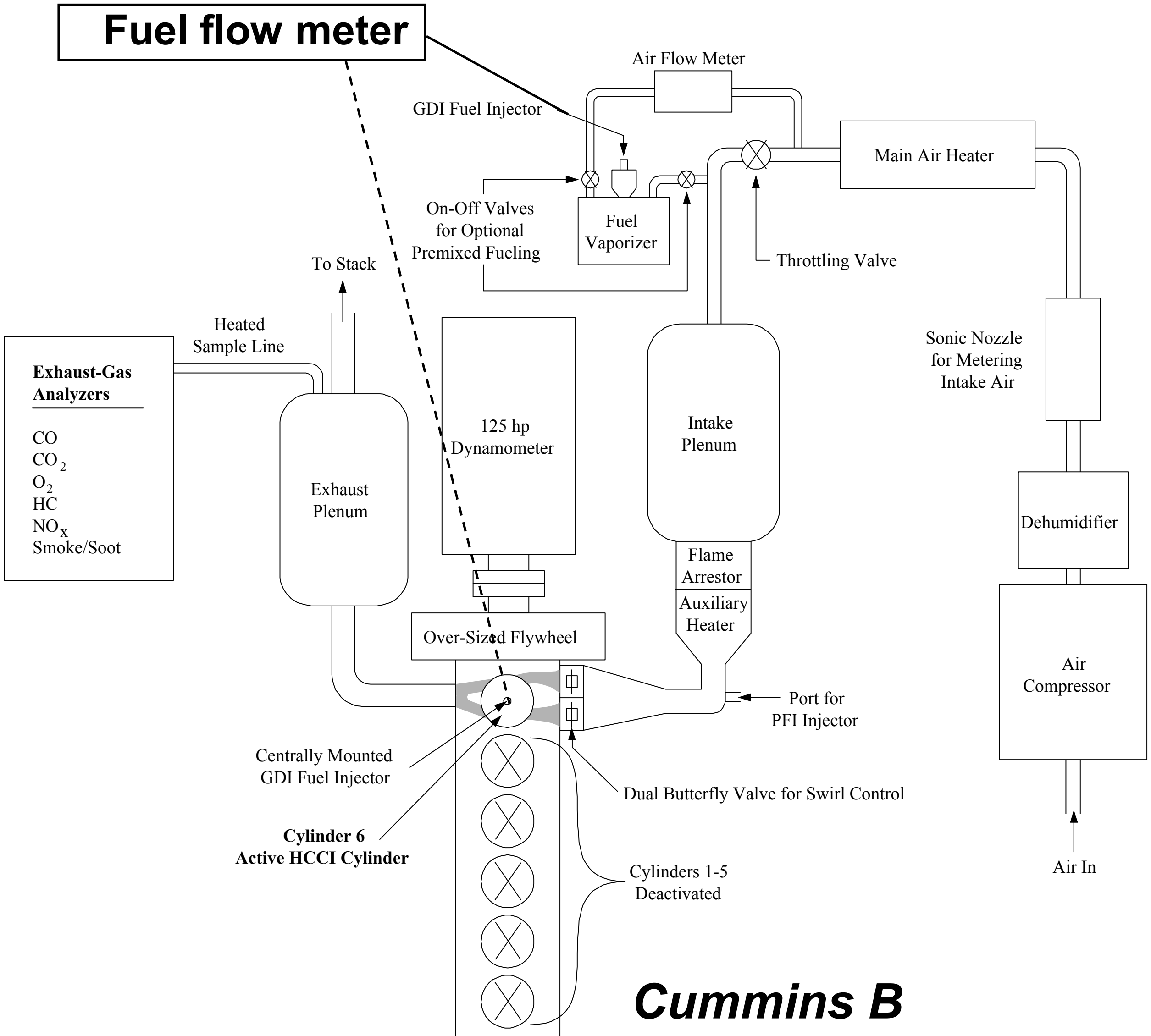


Based on Cummins B, 0.98 ltr./cyl.

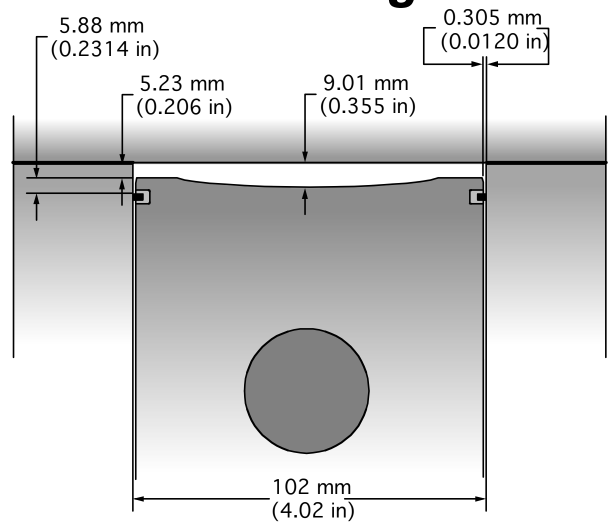
- Six-cylinder diesel engine converted for balanced, single-cyl., HCCI operation.
- Versatile facility to investigate various operational and control strategies.
  - Compression ratios from 13 - 21 (18)*
  - Swirl ratios from 0.9 - 3.2; 7.2 (0.9)*
  - Speeds to 3600 rpm (600 - 2400 rpm)*
  - Multiple fueling systems.
    - > Fully premixed (curr.)*
    - > Direct injection, gasoline-type (curr.)*
    - > Port fuel injection (PFI)
    - > Direct injection, diesel-type
  - Liquid or gas-phase fuels (liquid)*
- Complete intake charge conditioning.
  - Intake temperatures to 180° C. (varies)*
  - Intake pressures to 4 bars. (varies)*
  - Simulated or real EGR. (none)*

* Values in (red) are used for current work.

Metal HCCI Engine and Subsystems



Piston design:



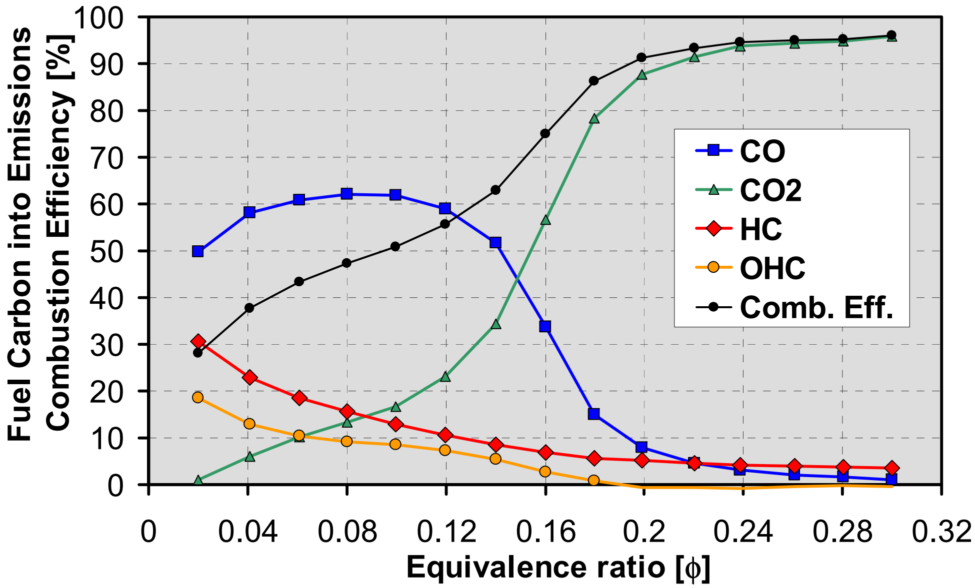
CR: 18

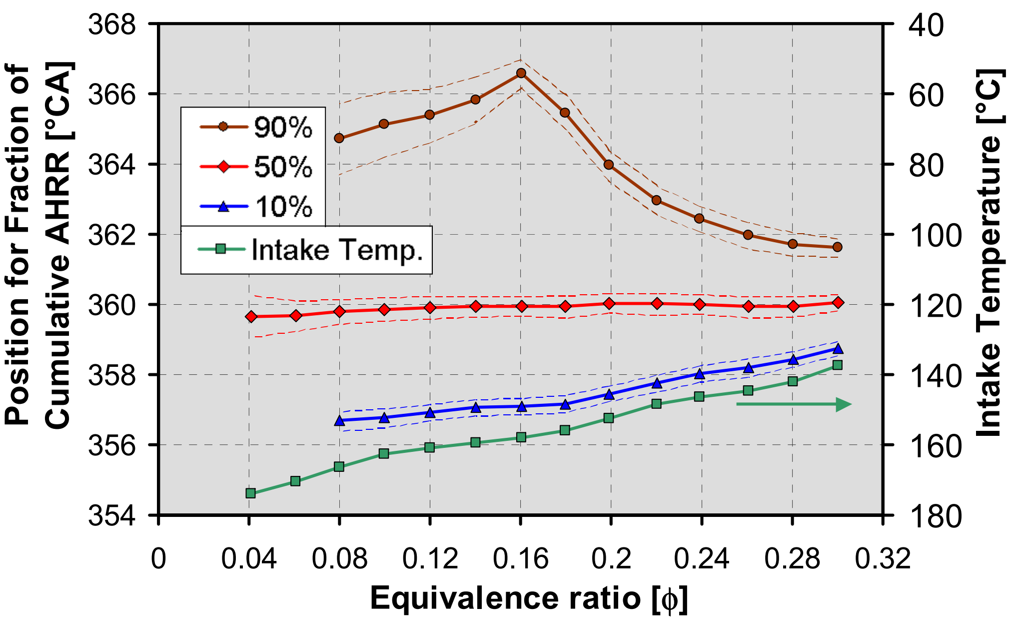
Swirl Ratio: 0.9

minimal crevice volume

Cummins B
0.98 liter / cyl.

Baseline Case: Iso-Octane, 1200rpm

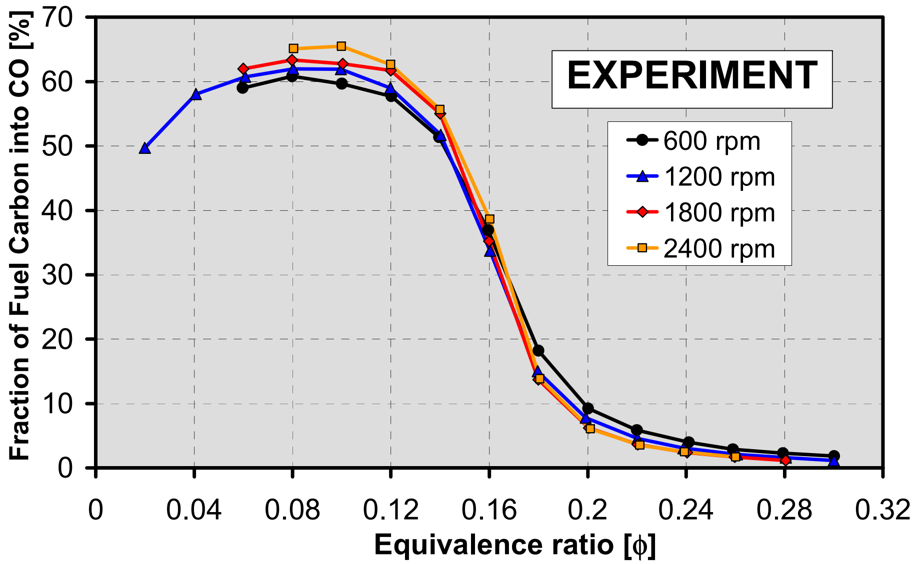


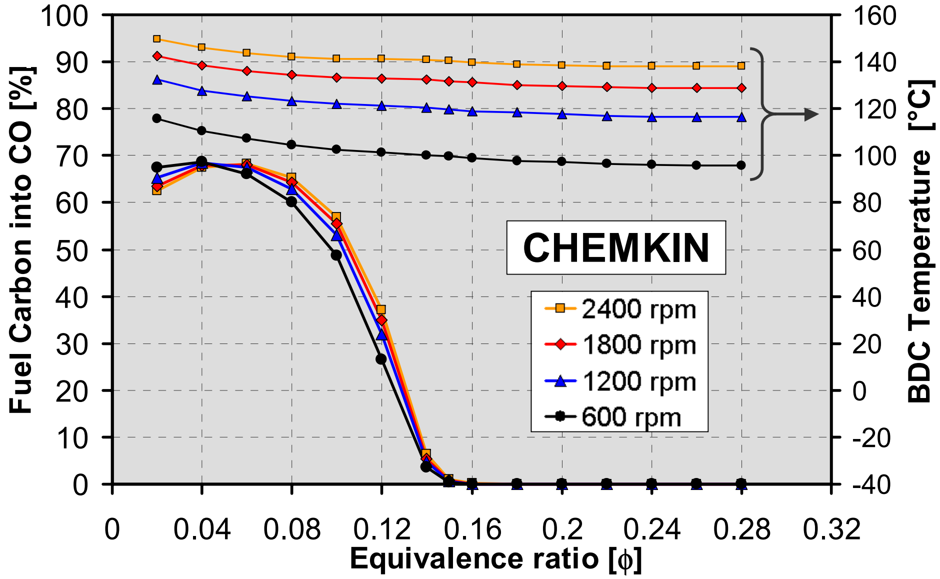


P_{in} = 100 kPa; Premixed Charge

- Onset of incomplete bulk-gas reactions for $\phi < 0.2$.
  - Peak temp. < 1500 K.
  - Desired op. range to $\phi = 0.12$.
- Stratification can improve.
  - DEER02 & SAE 2003-01-0752
- Important to understand how affected by speed & fuel-type.
- 50% burn maintained at TDC.
- This required increased intake temp. with decreasing load.
  - Slower burn, need to advance ignition.
  - Also changes in heat transfer, residual temp., chemistry, etc.

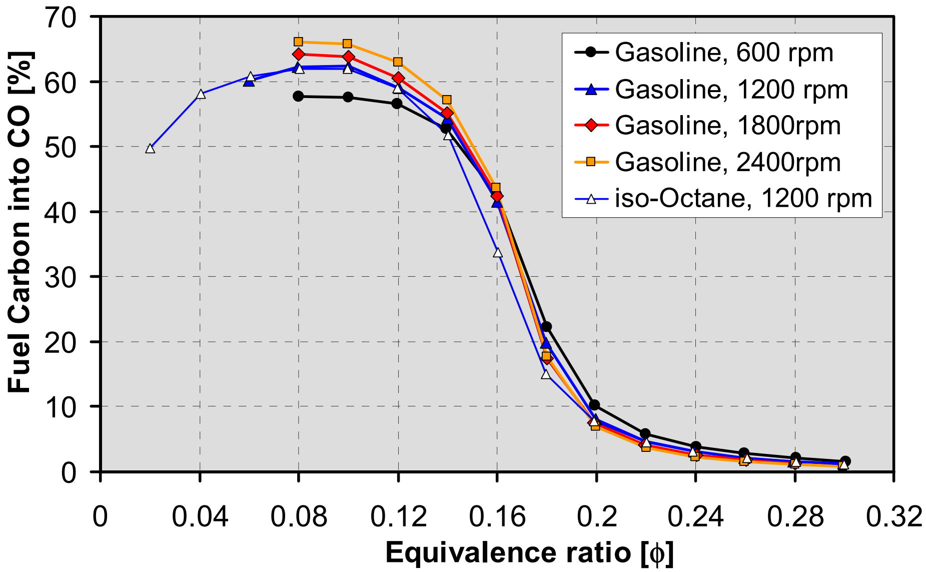
Effect of Engine Speed on CO-to-CO_2 Reactions

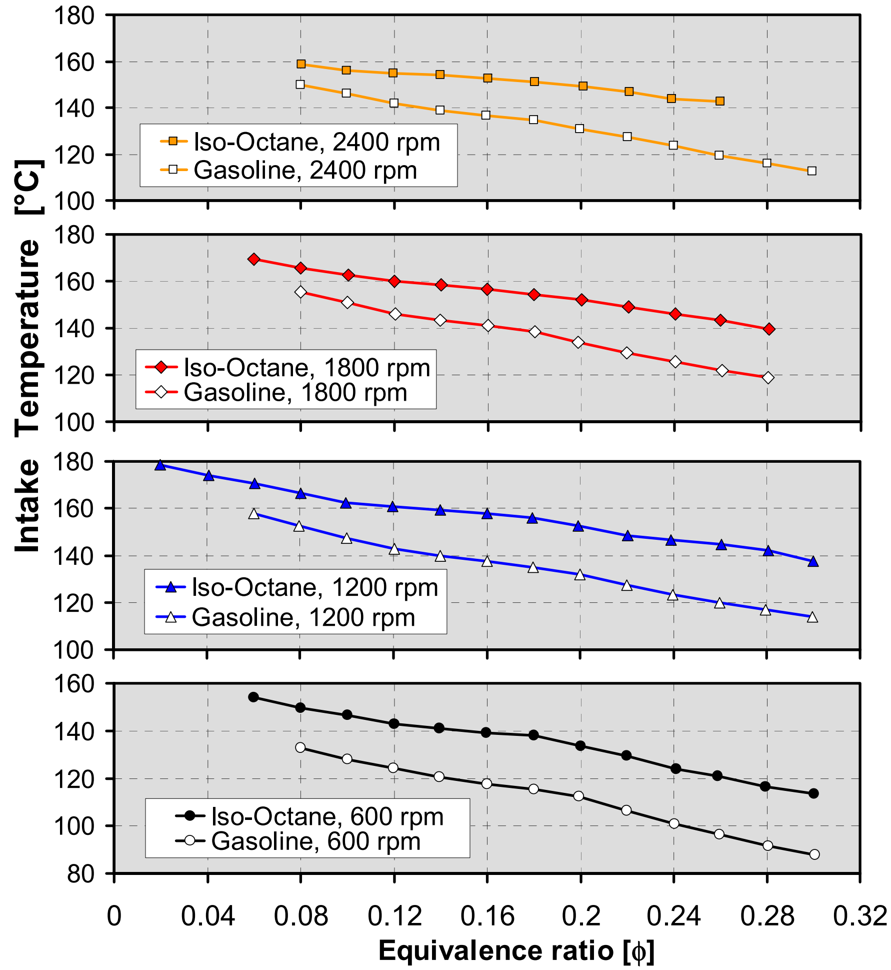




- For iso-octane, engine speed has an insignificant effect on the fueling rate at which the onset of incomplete CO-to-CO_2 reactions occurs.
- Also predicted by single-zone CHEMKIN model with detailed chemistry for iso-octane.
- Increased intake/compression temperatures to maintain ignition for increasing engine speed also speeds up the combustion.
  – Compensates for less time to complete the CO-to-CO_2 reactions.
- Reactions controlled by OH levels. Sensitive to relatively small changes in peak temperature: 1470 – 1550 K for 600 – 2400 rpm.

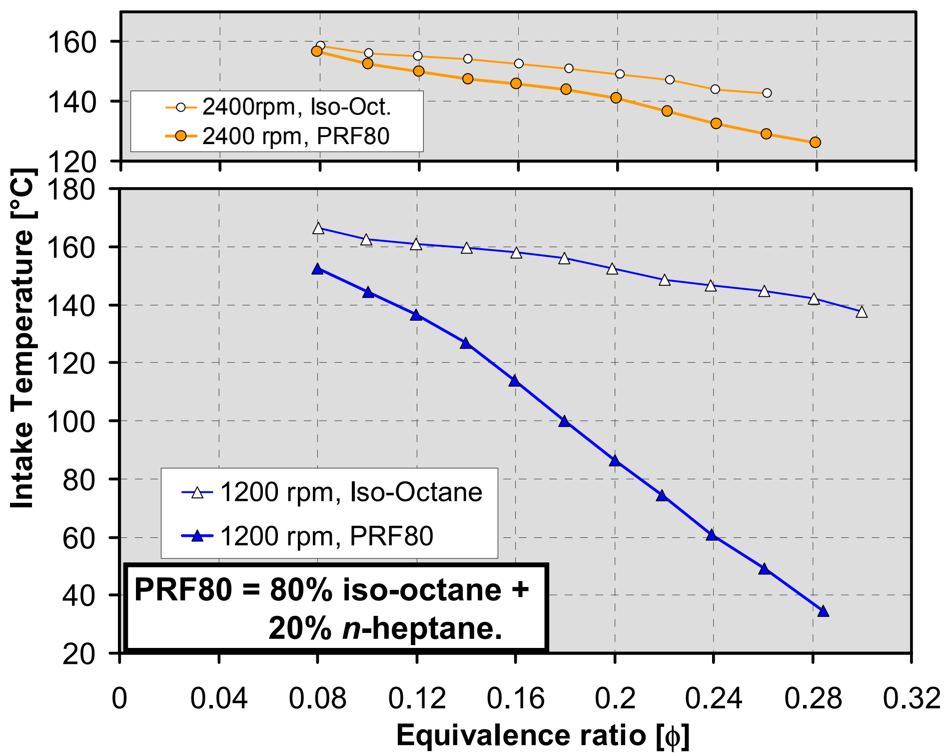
Gasoline vs. Iso-Octane

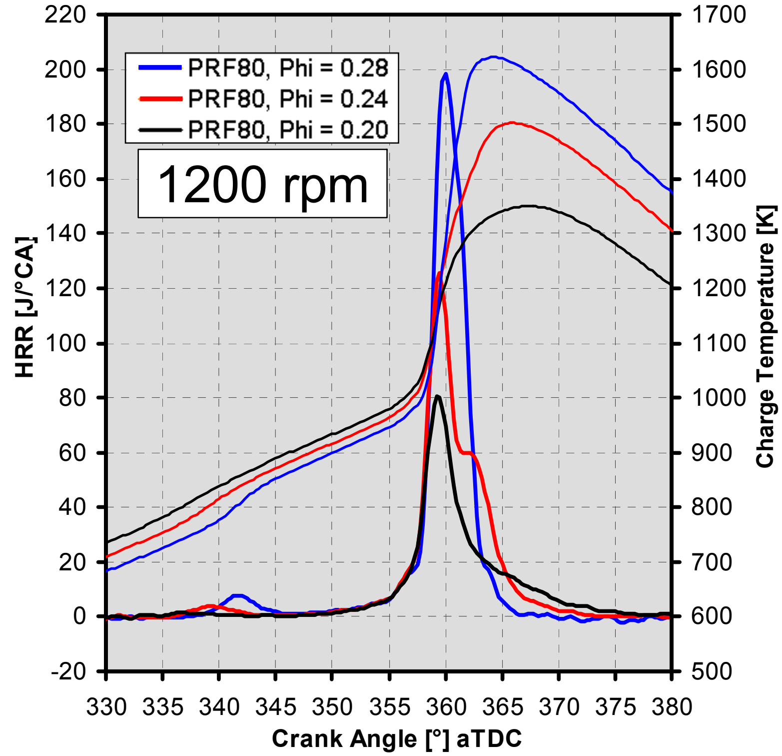




- Onset of incomplete CO-to-CO_2 reactions occurs at a slightly higher ϕ.
- Lower intake temperature for 50%@TDC for all speeds.
  - Slopes are quite similar.
  - ΔT ~20°C. Increases only slightly for decreasing engine speed & load.
  - Octane Index: (R+M)/2 = 87, vs. 100 for iso-octane.
- Examine PRF mixtures to better understand effect of octane number.

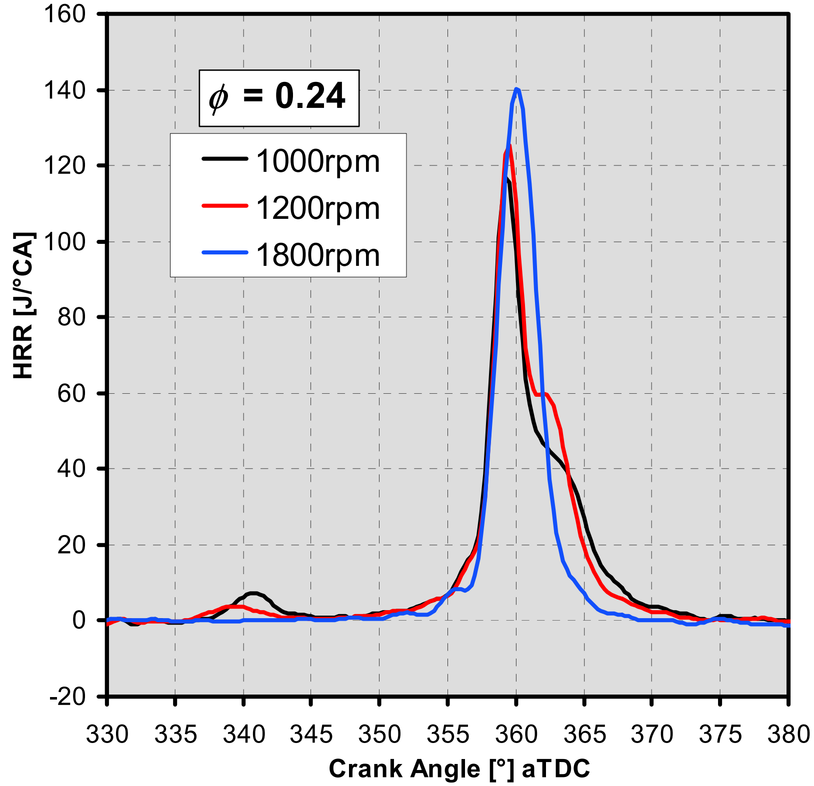
PRF80 vs. Iso-Octane – Load

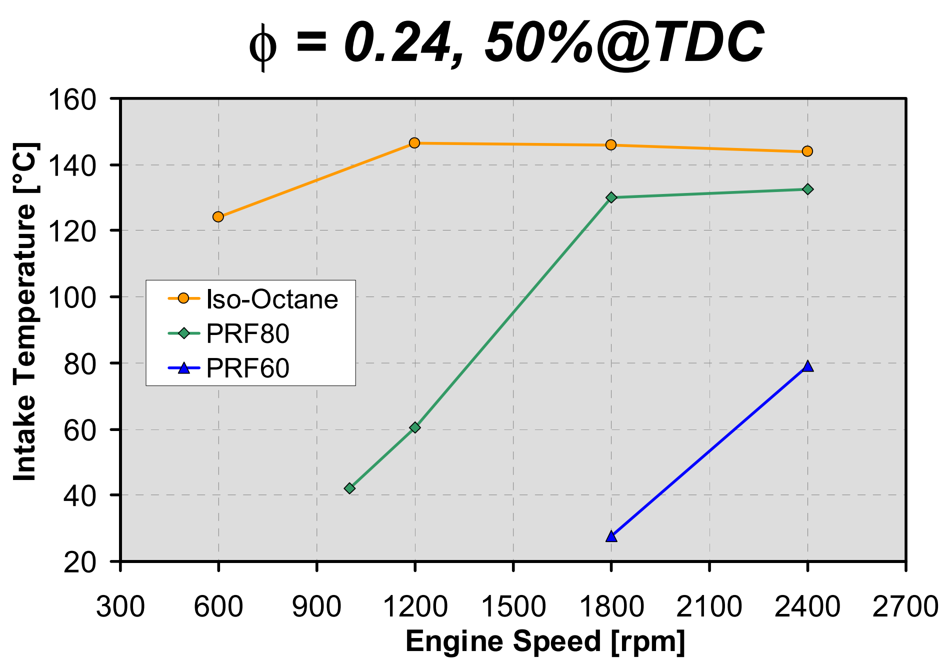




- Much lower intake temperature for PRF80 at 1200 rpm.
- Steeper slope. Increasing "cool-flame" activity with fueling.
  - Cool-flame activity with n-heptane is analogous to diesel-fuel ignition.
- Hot chemistry starts at about the same temperature.
  - Lower T_{in} needed because of heating effect of cool-flame activity.
- At 2400 rpm, intake temperatures are similar.
  - Little time for cool-flame chemistry to develop.

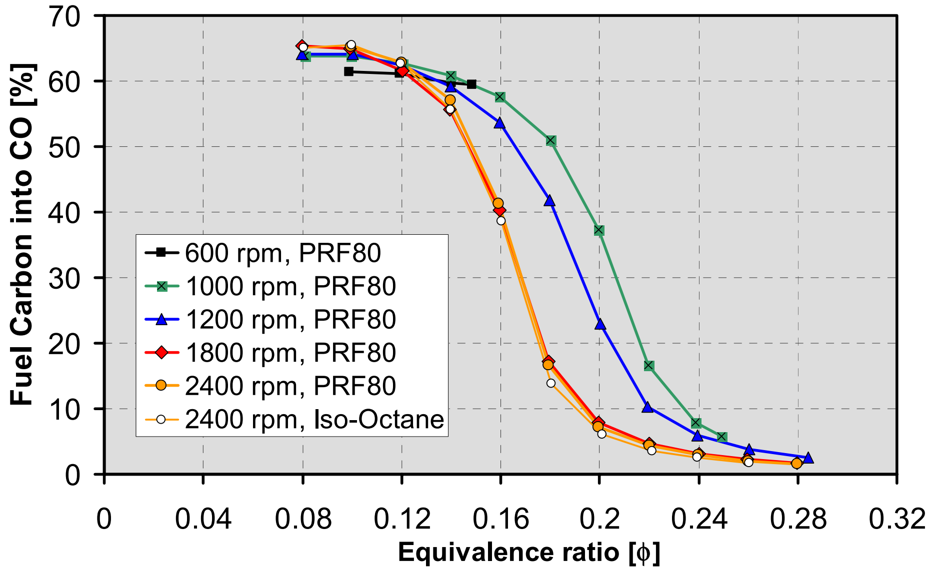
PRF80 vs. Iso-Octane – Speed

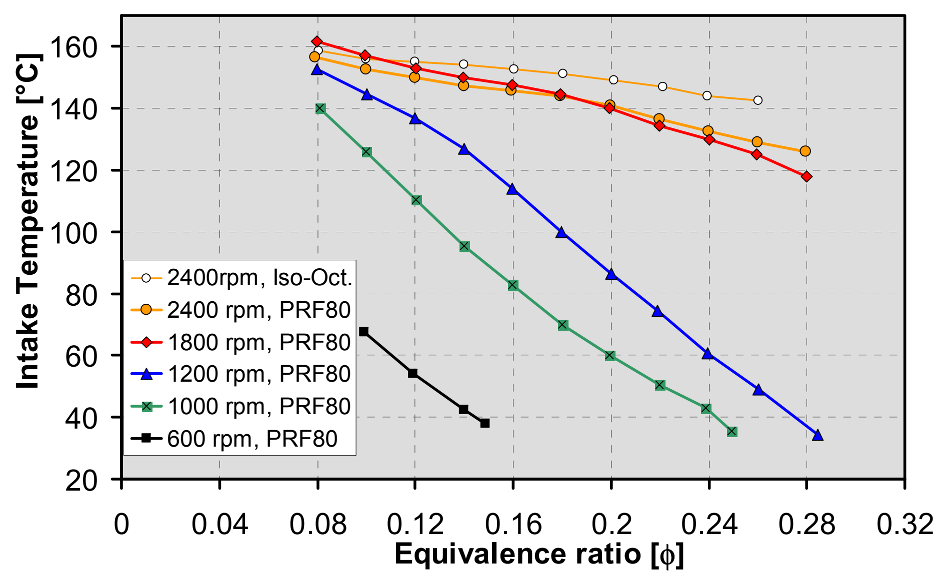




- Amount of cool-flame chemistry increases with lower engine speed.
  - More time for the slow low-temperature chemistry to develop.
- Significantly reduces required intake temperature at lower speeds.
- Cool-flame activity is highly non-linear with engine speed.
  - Breakpoint at 1800 rpm for PRF80, extrapolate to ~3000 rpm for PRF60.

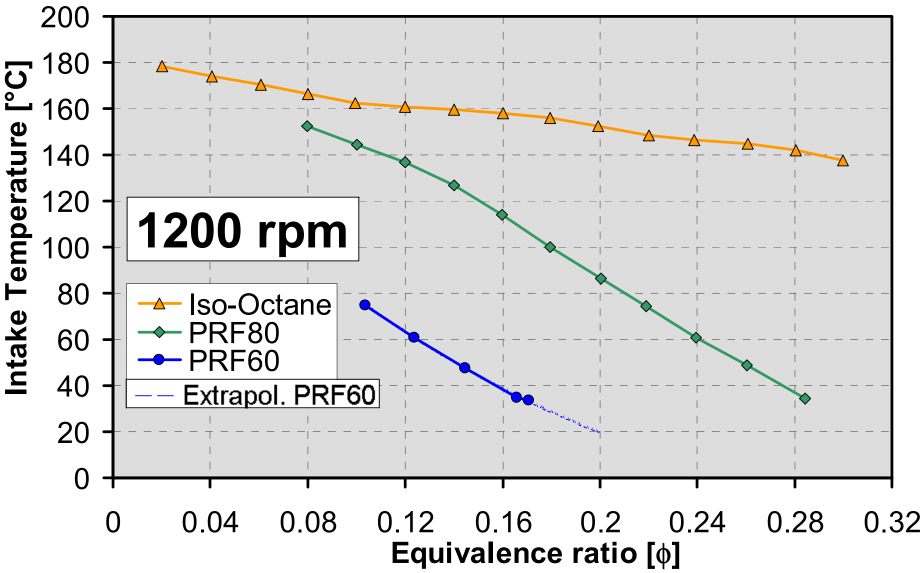
PRF80 – CO Emissions

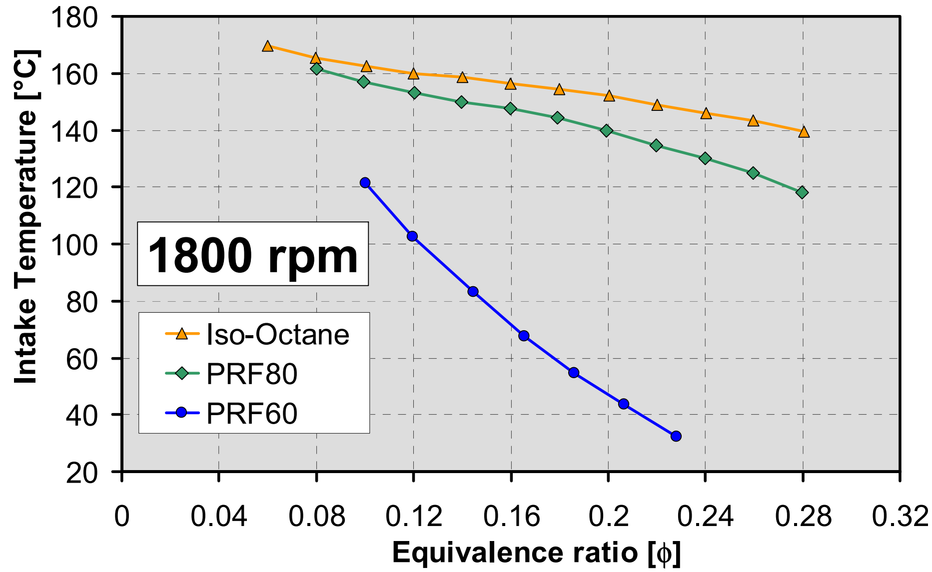




- The onset of CO-emissions is no longer independent of engine speed.
  - Shift to higher fueling for lower engine speed.
- Higher fueling is needed to reach ~1500K since the required intake temperature is lower at lower speeds.
- Only the low loads can be phased at TDC for 600 rpm.
  - Minimum intake temperature ~35°C.
- Below 1000 rpm, could not operate with combustion phasing at TDC and complete combustion (with this CR = 18:1).

Cool-Flame Activity vs. n-Heptane Content

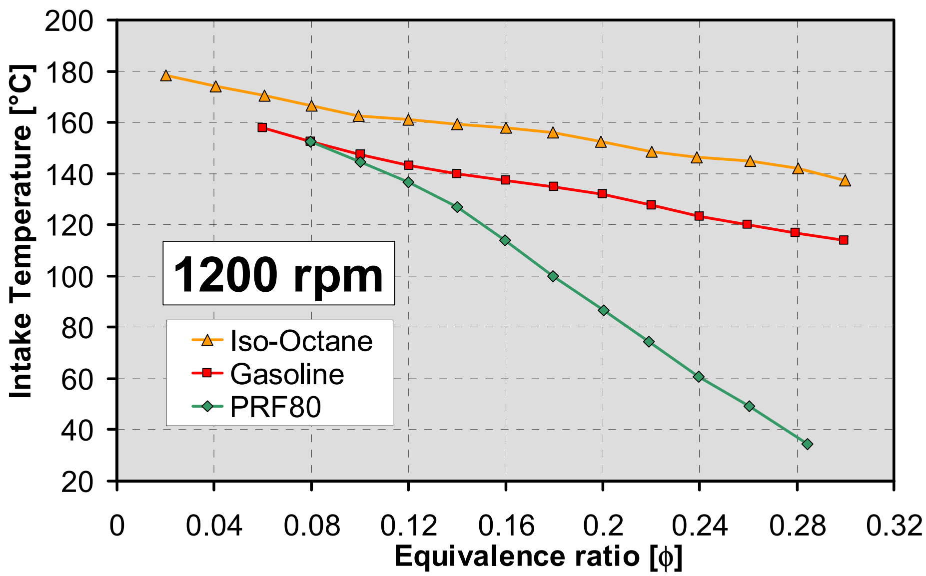


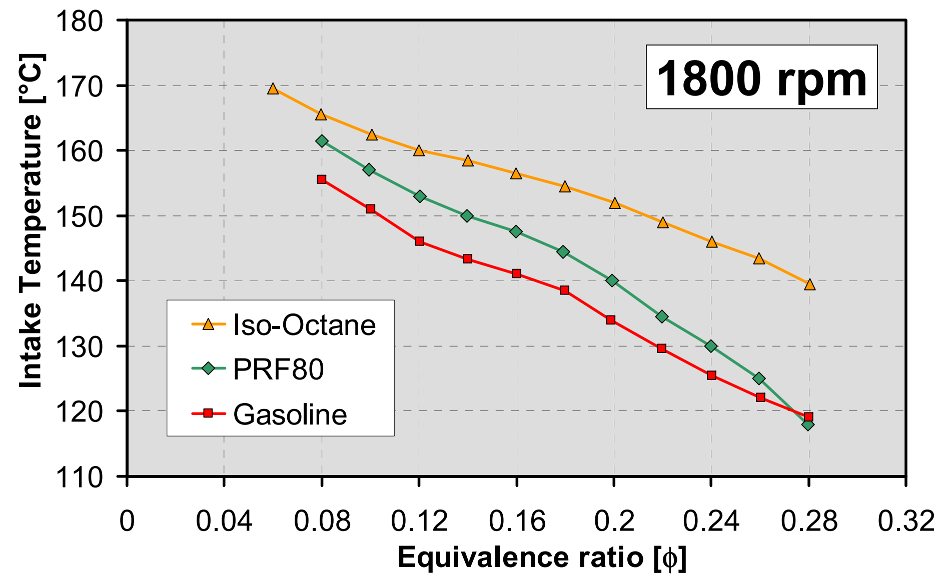


- Iso-octane never shows signs of cool-flame activity for the conditions covered here.
- Deviation from iso-octane can therefore be viewed as a measure of ignition enhancement of *n*-heptane. Caused by cool-flame activity.
- Cool-flame activity is proportional to *n*-heptane content only for $\phi \approx 0.20$, for 1200 rpm.
- For 1800 rpm, PRF60 shows roughly 7 times stronger cool-flame activity than PRF80.
- The cool-flame activity is highly non-linear with *n*-heptane content (ON).

Gasoline vs. PRF

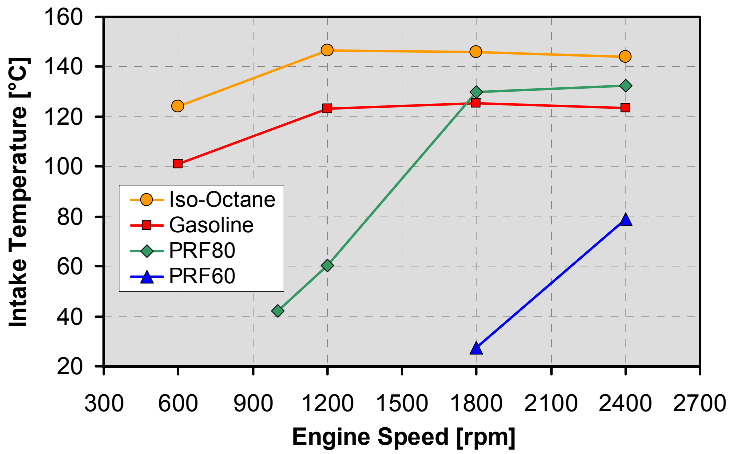
- RON = 90.8, MON =83.4, (R+M)/2 = Antiknock index = 87.1
- For 1200 rpm, the intake temperature is consistent with octane numbers. Except for the lowest fueling.
- For 1800 rpm, gasoline falls below PRF80!
- Octane number cannot be trusted for ranking fuels for HCCI autoignition.
- Fuels with cool-flame chemistry also require more adjustment of T_{in} to maintain phasing with changes in fuel load and speed.

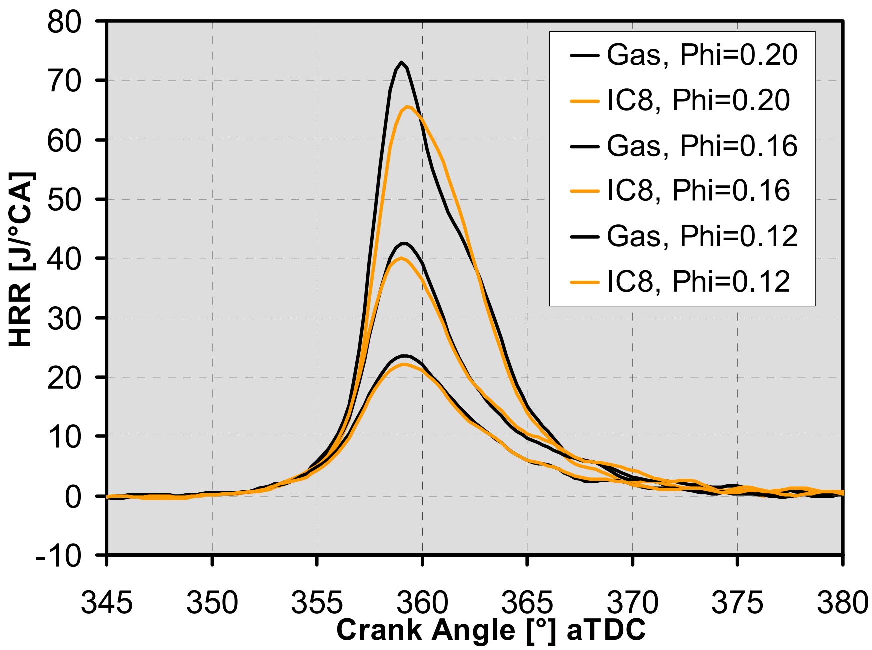


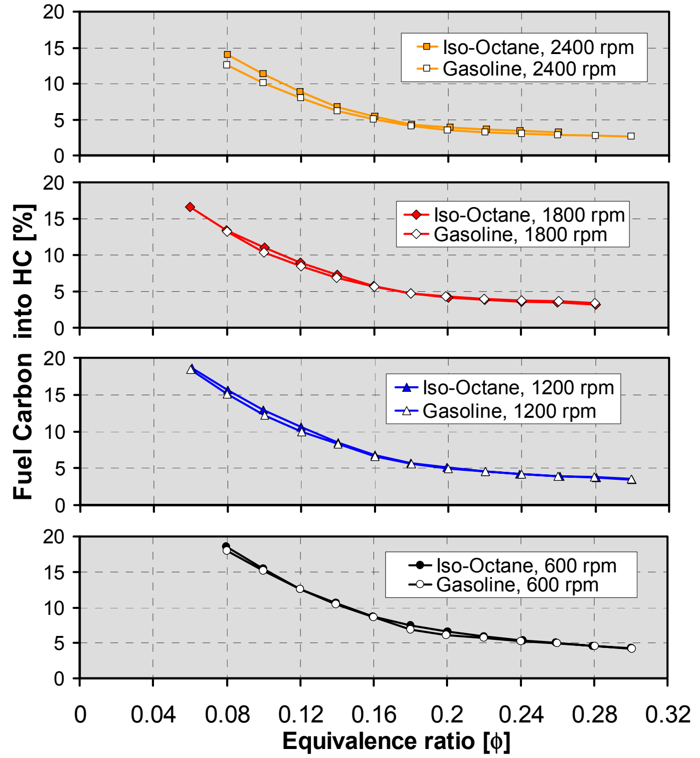


Iso-Octane as a Gasoline Surrogate

- Similar trends of T_{in} with engine speed.
- As a result, CO-emissions are similar, as shown above.
- HC-emissions are quite similar.
- Heat-release rates are similar.
  – No cool-flame activity.
- Iso-Octane is a good surrogate fuel for this gasoline, at conditions studied.







Summary and Conclusions - 1

- For complete combustion, peak temperatures must exceed a critical peak value of about 1500 K. (1470 – 1550K for 600 to 2400 rpm)

- Onset of incomplete combustion is independent of engine speed for both Iso-Octane and Gasoline.
  - Changes in intake/compression temperatures to maintain ignition timing compensate almost exactly for changes in time to complete combustion.

- Iso-Octane and Gasoline exhibit similar heat-release rates and HC-emissions.

- Both fuels require similar changes in T_{in} with changes in speed & load.
  - Required T_{in} for Gasoline is roughly 20°C lower.

- Iso-Octane is a good surrogate for this Gasoline for conditions tested.

Summary and Conclusions - 2

- Both PRF80 and PRF60 exhibit cool-flame heat-release.
  - As occurs with diesel-fuel autoignition.
- The amount of cool-flame activity increases with:
  - Lower engine speed.
  - Higher equivalence ratio.
  - Higher *n*-heptane content.
  - The changes are generally non-linear with the above parameters.
- With increasing cool-flame activity, the intake temperature must be decreased to maintain phasing.
  - Therefore, higher fueling required to reach ~1500K to complete CO-to-CO_2.
  - Shifts onset of incomplete combustion to higher loads, reducing op. range.
- Engine management for load and speed transients could be more complicated for fuels with significant cool-flame activity.
  - Due to the larger required changes in T_{in}.
- Octane number cannot be trusted for ranking the autoignition quality of different fuels for HCCI operation.