

Factors Affecting HCCI Combustion Phasing for Fuels with Single- and Dual-Stage Chemistry

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Introduction



- HCCI engines can provide diesel-like efficiencies and ultra-low NO_x and PM emissions – However there are several technical barriers.
- Control of combustion phasing with changes in fueling rate is particularly important.
 - Various control techniques are available: intake heating, VCR, VVT.
 - Ultimately adjust the compressed-gas temperature (T_{CG}) at “ignition.”
- Often considered that combustion phasing can be affected by F/A mixture \Rightarrow Ignition is faster with richer mixtures created by higher fueling rates or charge-mixture inhomogeneities.
- However, as the fuel load is varied, several factors are affected, each of which can affect combustion phasing.
 - Most factors directly or indirectly cause changes in the T_{CG} .
 - Additionally, these factors can sometimes mask changes – or lack of changes – due directly to F/A-mixture effects.

Objectives

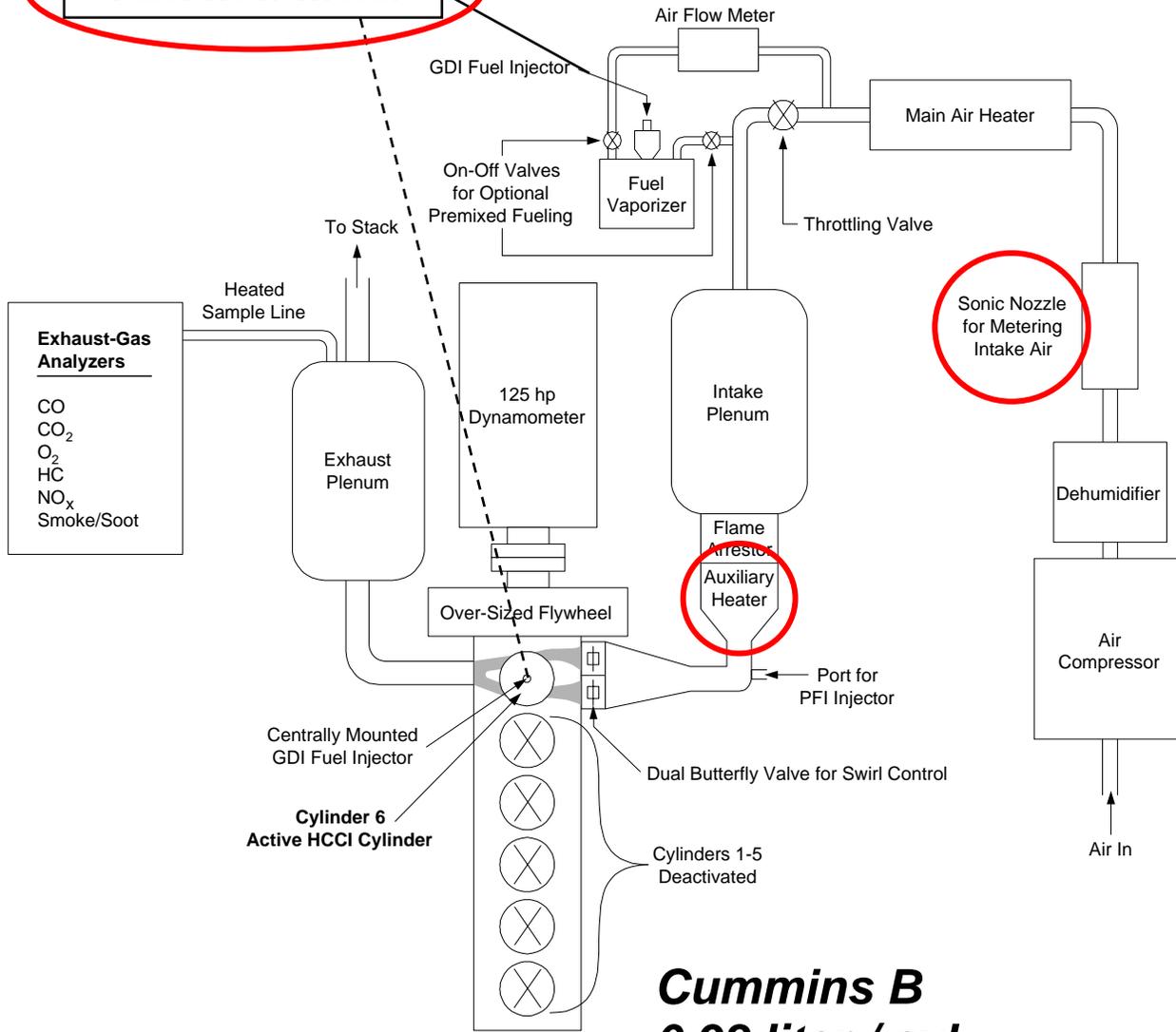


- Identify the factors that cause changes in combustion phasing with changes in fueling rate (fuel-air equivalence ratio, ϕ).
- Systematically remove the changes due to each factor.
 - Understand the relative magnitude of these factors.
- Isolate the effect of changes in fuel chemistry with equivalence ratio to understand the importance of this factor.
 - Compare behavior of various fuel-types: iso-octane, gasoline, & PRF80.
- Investigate the potential of fuel stratification for controlling combustion phasing.

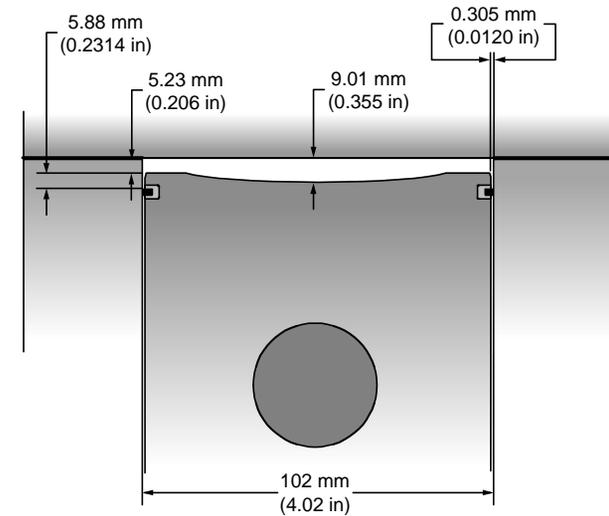
HCCI Engine and Subsystems



Fuel flow meter



Piston design:



Base Condition

CR: 17.6

Swirl ratio: 0.9

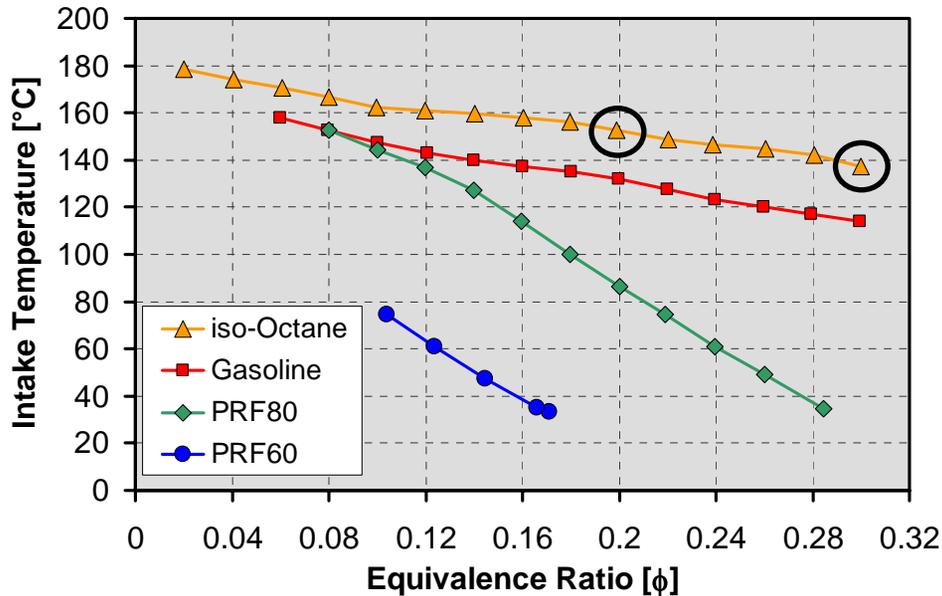
Speed: 1200 rpm

P_{in} : 100 kPa

Fueling: Premixed
GDI

Cummins B
0.98 liter / cyl.

Observed Changes with Variation in Fueling



- As fueling (ϕ) is varied, T_{CG} must be adjusted to maintain combustion phasing.

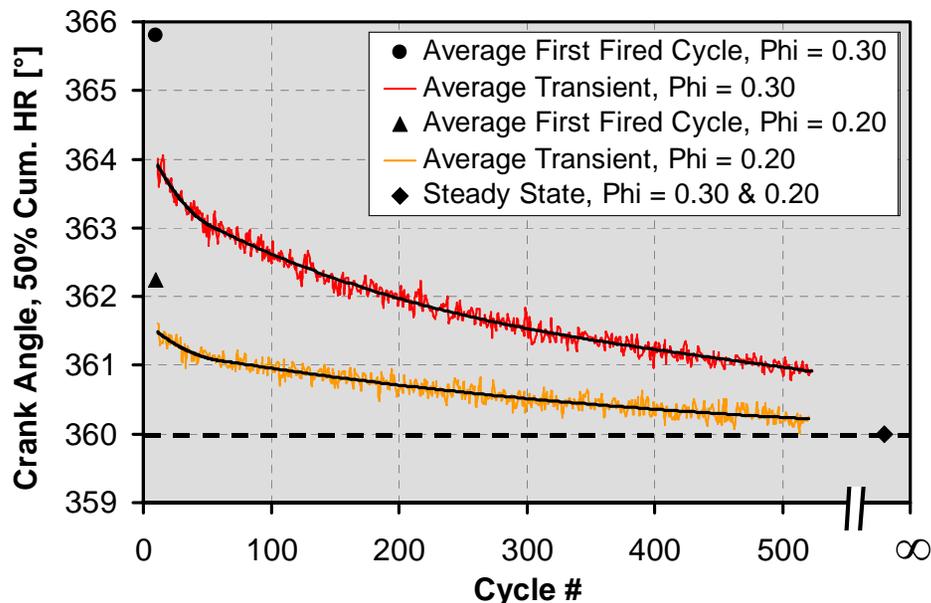
- 50%-burn phasing at TDC (indication of performance).
- Adjust T_{CG} by varying Intake temperature (T_{in}).

- All fuels show a trend of a lower required T_{in} with increased ϕ .

- Do richer mixtures autoignite more easily for all fuels?
- What role do other factors play?

- For example, wall heating and residuals will change with ϕ .

- Figure shows fuel-on transients for $\phi = 0.2$ and 0.3 , iso-octane (avg. of 10 events).

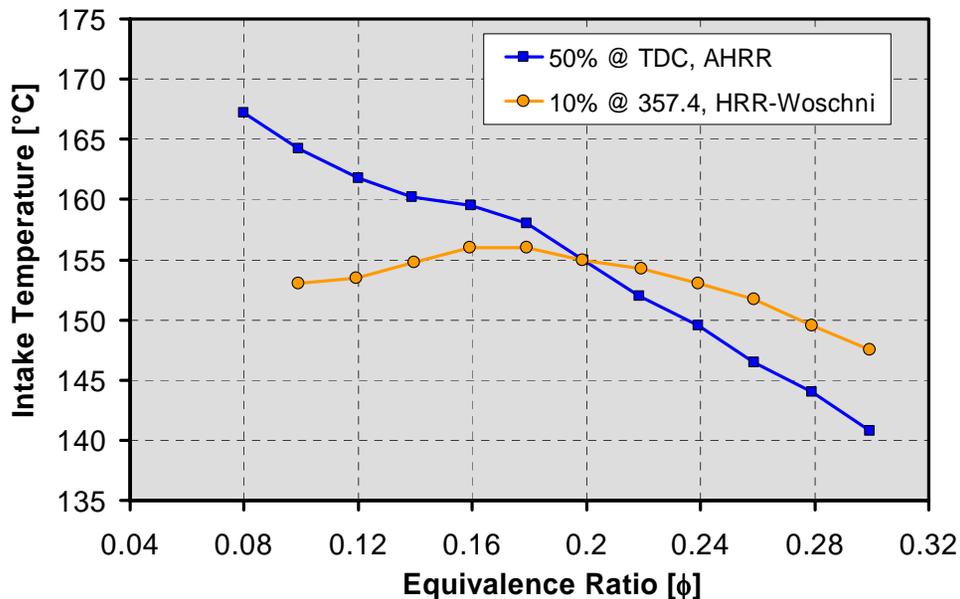
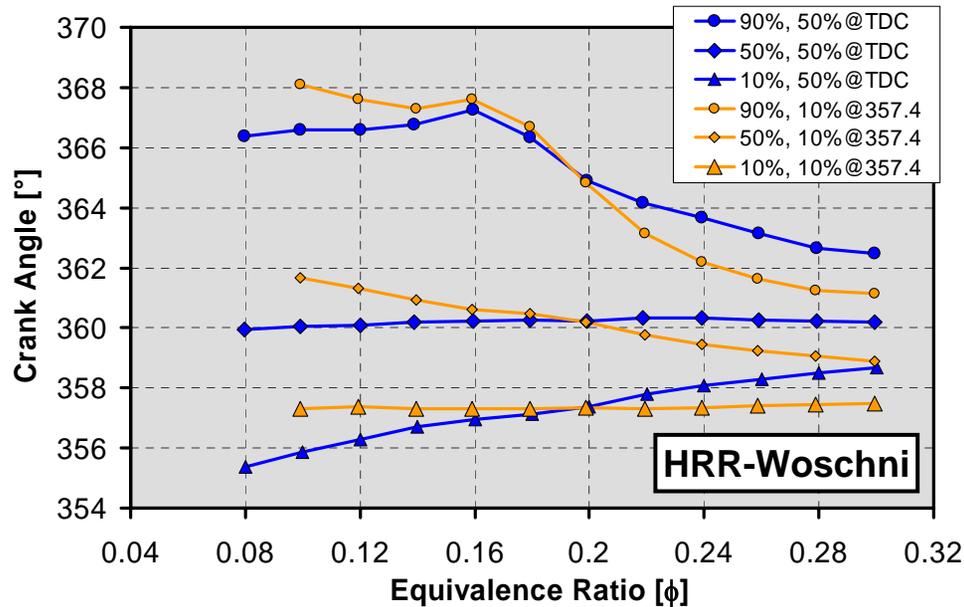


Factors Causing Changes in T_{in} with Fueling



1. Combustion duration increases at lower ϕ . This requires that the start of combustion occur earlier to maintain 50% burn at TDC.
 2. Wall temperatures increase with increased ϕ , causing higher T_{CG} for a given T_{in} .
 3. Temperature of residuals increases with ϕ , reducing required T_{in} .
 4. Heating/cooling during induction changes with ϕ as the ΔT between T_{in} and T_{wall} varies, amount of fuel vaporization, & “dynamic heating.”
 5. Fuel-chemistry effects.
 - Differences in ϕ can affect the chemical-kinetic rates of autoignition.
 - Thermodynamic properties of mixture – particularly specific heat ($\gamma=c_p/c_v$).
- Systematically remove factors 1-4 leaving only fuel-chemistry effects.
 - Evaluate differences in fuel chemistry: iso-octane, gasoline, & PRF80.

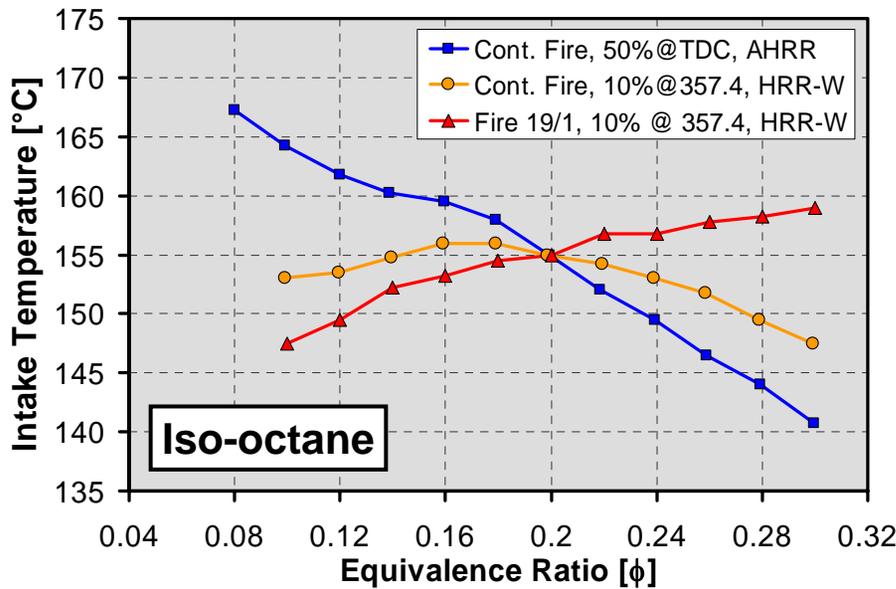
1. Changes in Combustion Duration



Base Fuel: Iso-Octane

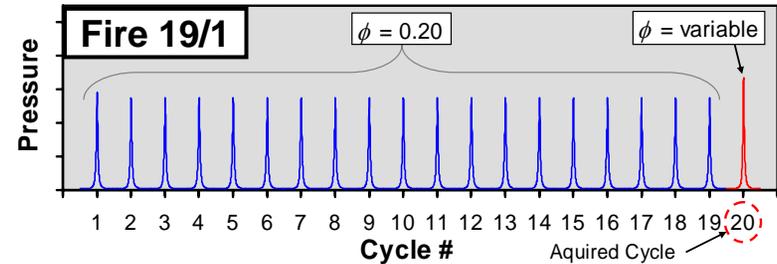
- Burn duration increases as ϕ reduced.
 - Phasing remains very stable – Std. Dev < 0.3°CA for 10 & 50% burn over range of interest.
 - $0.1 < \phi < 0.3$ (idle to moderate load).
- Fuel-chemistry effects should correlate with ignition point.
- Select 10% burn as “ignition” pt.
 - Use Woschni correlation to account for heat transfer.
- Retake data with const. 10% burn at 357.4°CA, match $\phi=0.2$.
 - Change in T_{in} with ϕ is greatly reduced, from 24°C to 8.5°C.

2 & 3. Remove Changes in T_{wall} and Residuals



- Remove changes in T_{wall} & residuals using alternate-firing technique.

– Hold 10% burn phasing at 357.4°.



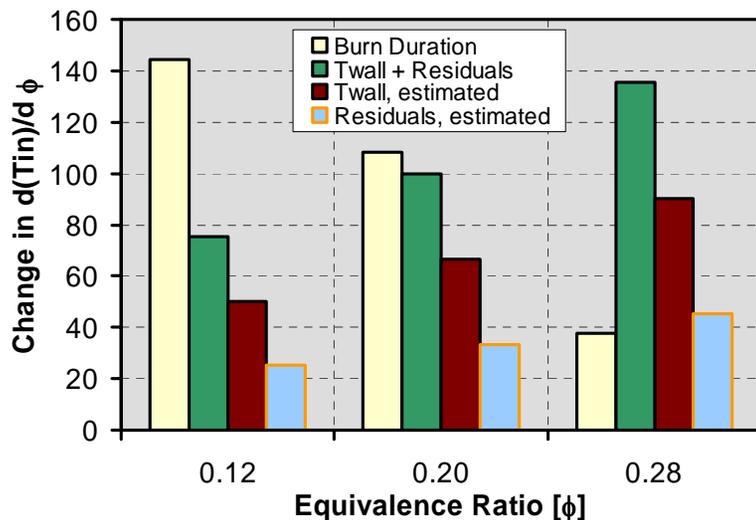
- Reverses trend – higher T_{in} with higher ϕ .

- Change in slope between the curves gives relative magnitude of factors.

– $\phi < 0.2$, burn duration dominates. comb. eff. low: long burn, low heating.

– $\phi > 0.2$, opposite is true.

- Separate T_{wall} & residual effects estimated from transient data and fire18/2 data.

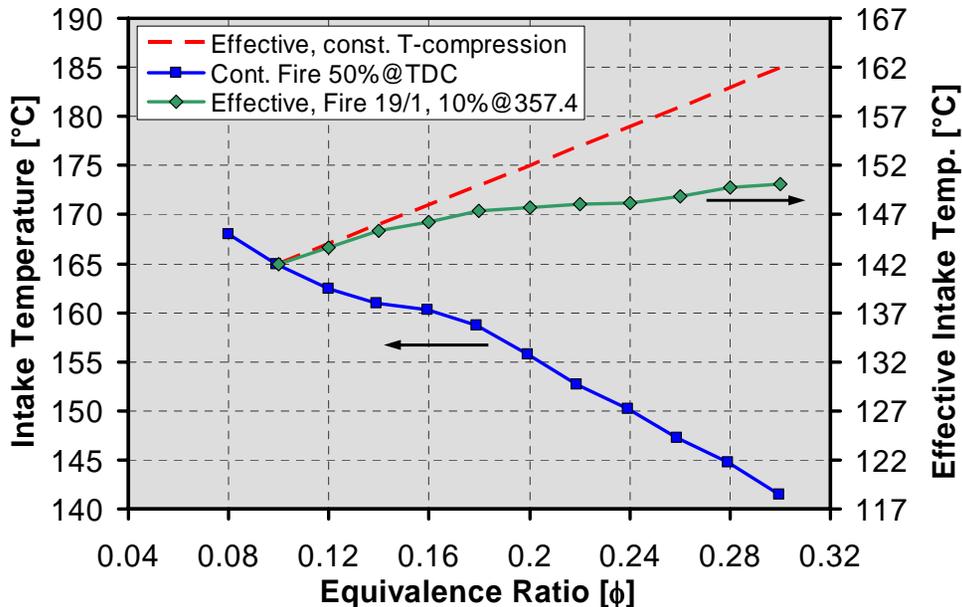
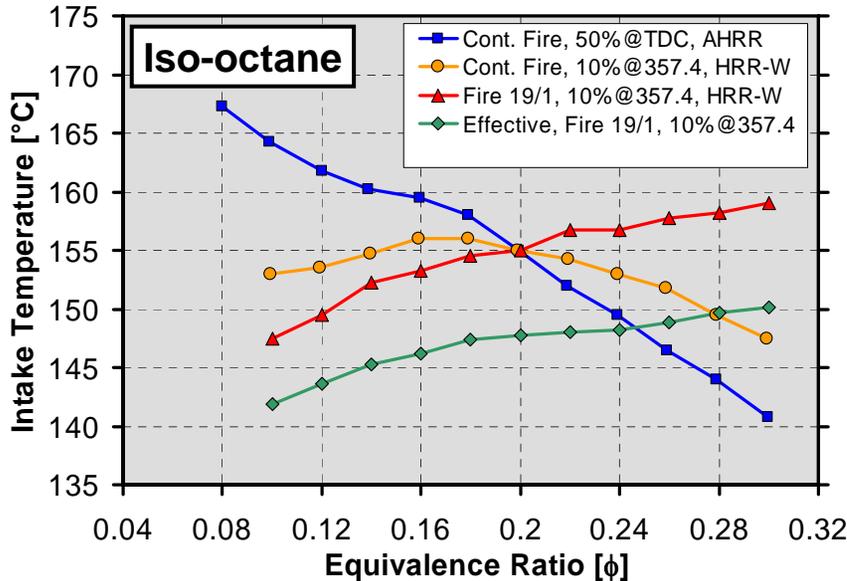


4. Heating/Cooling During Induction



- $T_{in} \neq T_{BDC}$ due to heating/cooling during induction.
- Developed technique to estimate $T_{BDC} \Rightarrow$ Details in SAE 2004-01-1900.
- Compute changes in T_{BDC} from measured changes in mass flow relative to a base condition.
- Ideal gas law gives:
$$T_{in, effective} = T_{in, effective, base} \cdot \frac{m_{air, base}}{m_{air+ fuel}} \cdot \frac{M_{air+ fuel}}{M_{air}} \cdot \frac{P_{in}}{P_{in, base}} \uparrow^1$$
- Base condition: motored $T_{in} = T_{coolant} = 100^\circ\text{C}$, minimizes heat transfer.
 - Dynamic heating $\Rightarrow T_{BDC, base} = 110^\circ\text{C}$ (from WAVE code, Ricardo).
- Estimate $T_{residuals} \approx$ average of $T_{exhaust}$ and $T_{blowdown}$.
- Combine to get:
$$T_{bdc} = \frac{T_{in, effective} \cdot m_{air+ fuel} + T_{residuals} \cdot m_{residuals}}{m_{air+ fuel} + m_{residuals}}$$
- A straightforward procedure. Technique is very sensitive.

4 & 5. Use T_{BDC} to Isolate Effects of Fuel Chemistry

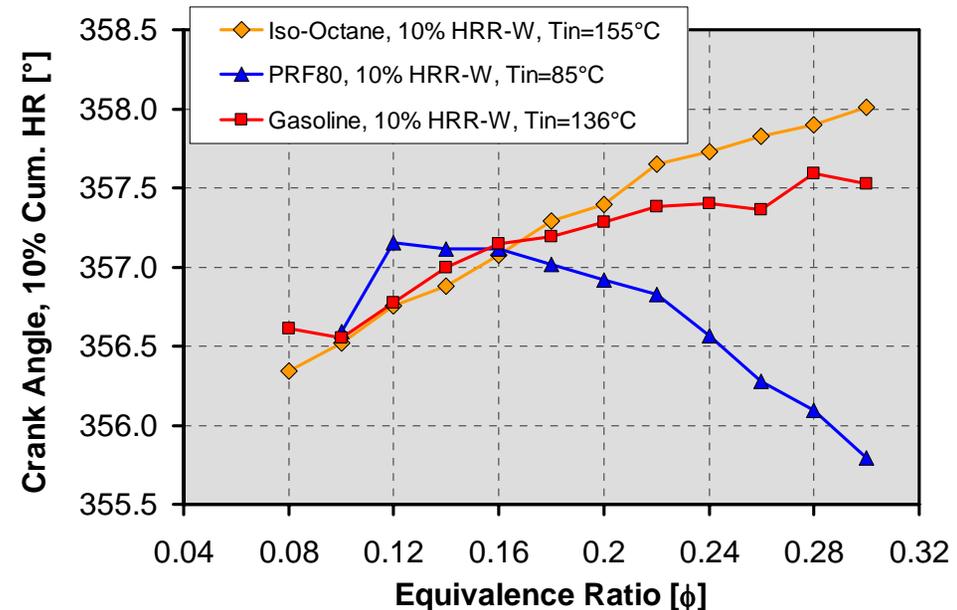
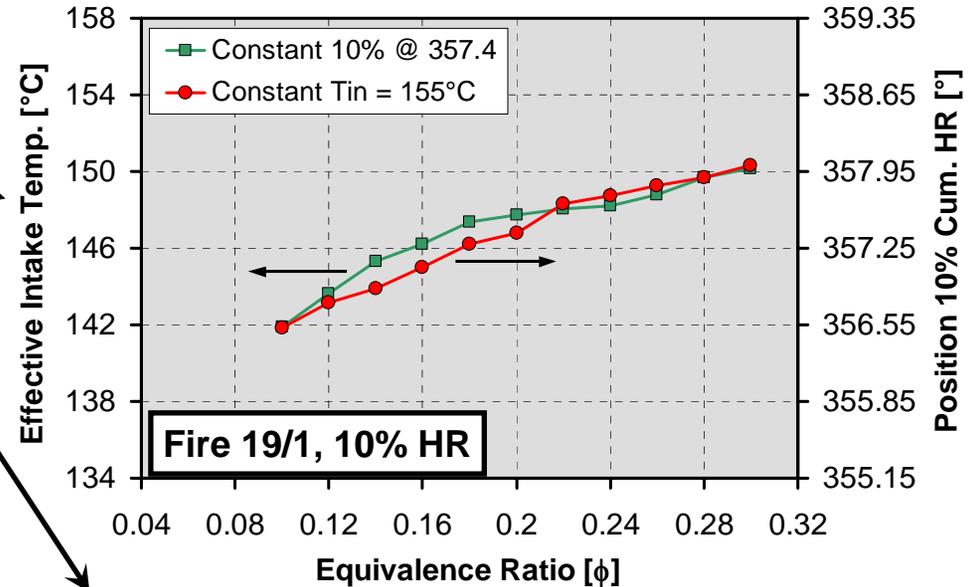


- For fire19/1, residuals are constant; use effective T_{in} rather than T_{BDC} .
- Effective T_{in} curve shows only changes due to fuel-chemistry.
 - Autoignition kinetics & $\gamma = c_p/c_v$.
- Does a higher ϕ enhance autoignition for iso-octane?
 - Higher $\phi \Rightarrow$ smaller $\gamma \Rightarrow$ higher T_{in} required for same T_{CG} .
- Lesser slope of Effective T_{in} curve indicates an enhancement with ϕ .
 - Effect fairly small for iso-octane.
 - > Much less than sum of other four factors.
 - Single-stage ignition fuel.

5. Fuel-Chemistry Effects – Various Fuels



- Alternatively, hold T_{in} constant and observe changes in phasing.
 - Trends similar to effective T_{in} .
- The 10%-phasing curves show isolated fuel-chemistry effects.
- Iso-octane: enhancement of ignition kinetics < effect of γ .
- Gasoline: a little more enhancement of ignition kinetics with increased ϕ than iso-octane.
- PRF80: autoignition kinetics greatly enhanced with ϕ .
 - Correlates with increasing cool-flame chemistry with ϕ (infers diesel fuel).
 - At low ϕ cool-flame activity is minimal, and trend is similar to iso-octane.



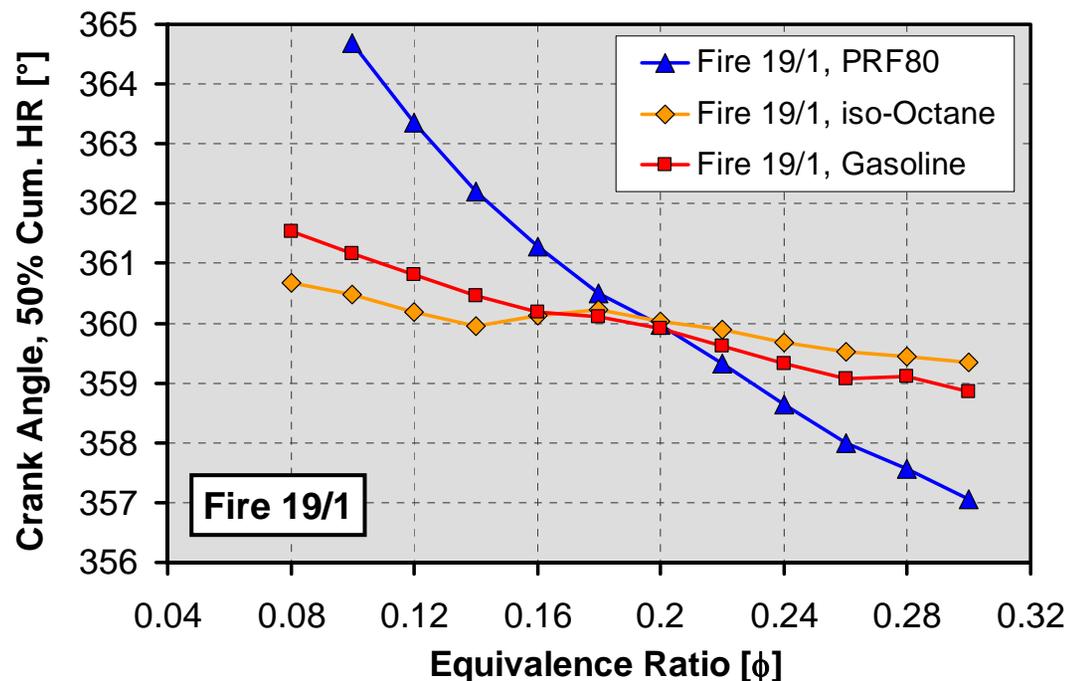
50% Burn Phasing for Constant T_{in} and T_{wall}



- 50% burn is a better indicator of engine performance.

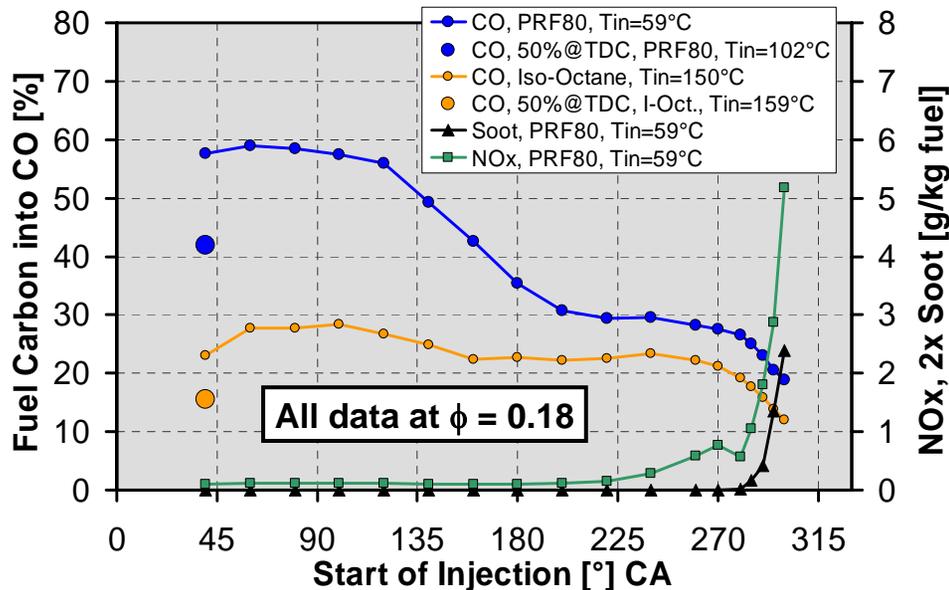
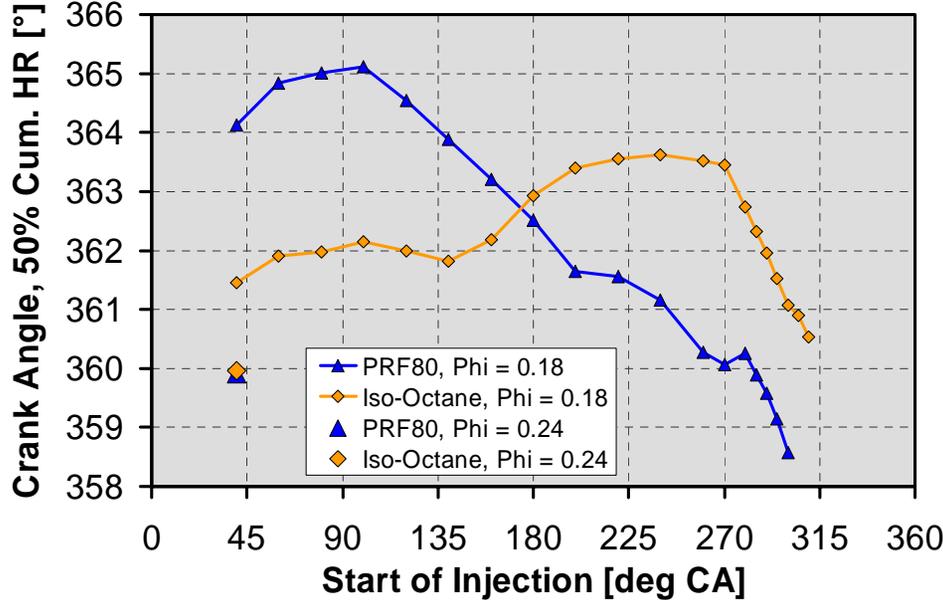
- Fire 19/1 data simulates behavior during a rapid load change before T_{in} and T_{wall} can respond.

- Iso-octane & gasoline: small variation, little compensation required. \Rightarrow single-stage ignition
- PRF80: large variation, significant compensation required. \Rightarrow dual-stage ignition (cool-flame chem.)



- Data can also be interpreted as indicating the potential for changing combustion phasing with mixture stratification (T_{wall} & residuals constant).
 - PRF80: mixture stratification has a strong potential to control phasing.
 - Iso-octane and gasoline: stratification offers little benefit for phasing control.

Stratification Advances Combustion for PRF-80



- PRF80: simulate load change from $\phi = 0.24 \Rightarrow 0.18$.
 - $\phi = 0.24$, $T_{in} = 59^{\circ}C$ for 50% burn at TDC.
 - $\phi = 0.18$, $T_{in} = 102^{\circ}C$ for 50% burn at TDC.
- Stratification can rapidly adjust phasing for PRF80.
 - Injection at $270^{\circ}CA$, in phase.
 - Also, improves combustion eff., as shown in SAE 2003-01-0752.
- Iso-octane: stratification does not advance phasing.
 - Weak enhancement of autoignition kinetics with ϕ .
 - Does not overcome charge cooling due to vaporization.

Summary and Conclusions



- In addition to fuel-chemistry, several factors affect the change in intake-temperature required to maintain constant 50%-burn phasing when the fueling rate is varied.
- The relative magnitude of these factors depends on the load range.
 - At low loads, ($\phi < 0.2$), changes in burn duration have the largest effect.
 - For higher loads ($\phi > 0.25$), changes in T_{wall} are dominant.
- The effect of residuals is relatively small in this engine.
 - They could be the dominant factor in a high-residual engine.
- The effect of F/A mixture (ϕ) on ig. timing depends strongly on fuel type.
 - Single-stage ignition fuels: iso-octane & gasoline \Rightarrow effect is small.
 - Dual-stage ignition fuels: PRF80 \Rightarrow effect is substantial due to cool-flame chemistry. (Similar effect expected for diesel fuel.)
- Mixture stratification can significantly and rapidly advance combustion phasing for PRF80 (or by inference diesel fuel), but not for iso-octane.