The Effects of EGR and Its Constituents on the Autoignition of Single- and Two-Stage Fuels

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Introduction

- Advanced LTC diesel and HCCI engines can provide both high efficiencies and very low emissions of NO_X and PM.

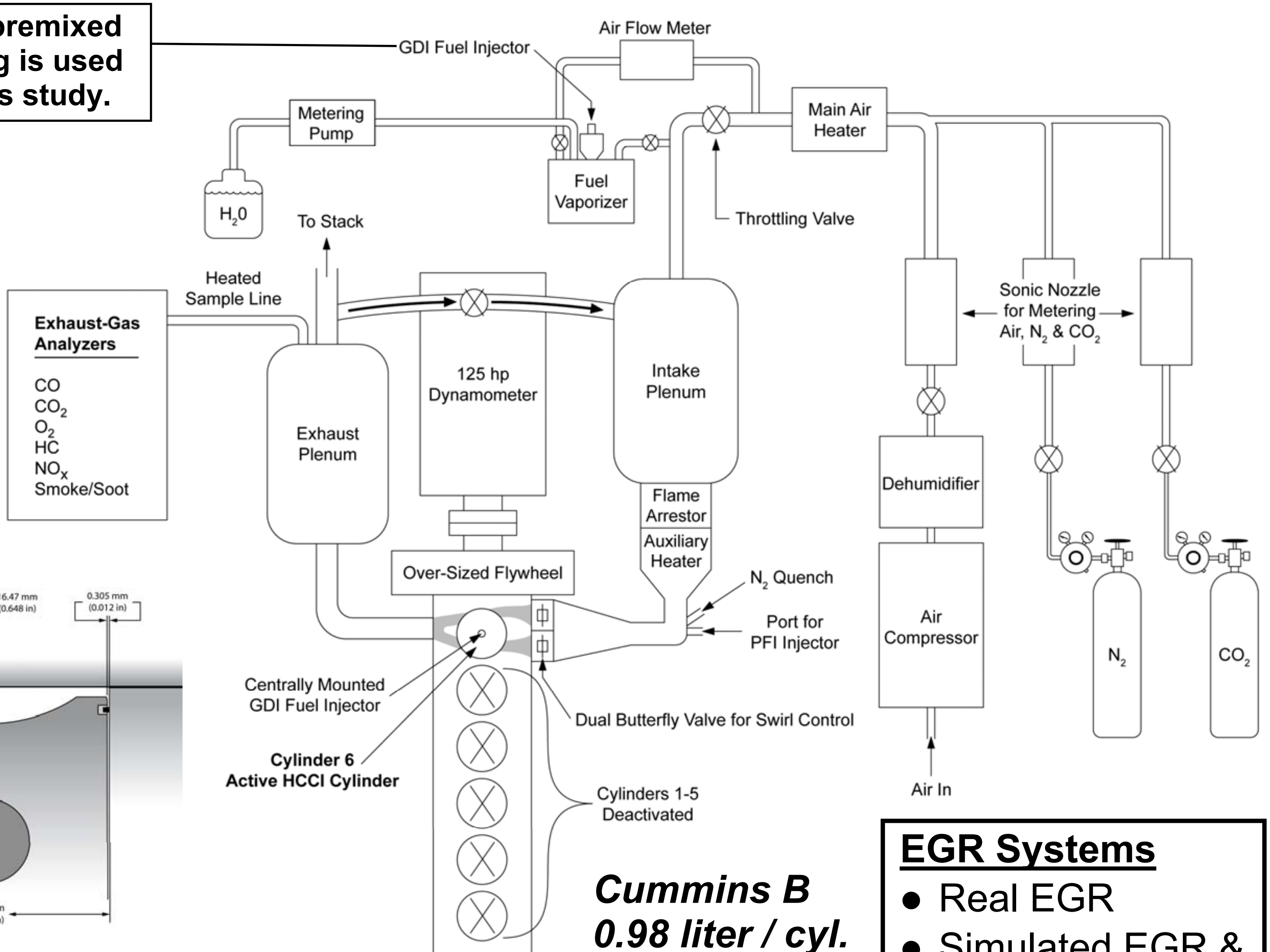
- Nearly all LTC and HCCI strategies use high levels of EGR/residuals.
  1. Reduce peak combustion temperatures to control NO_X.
  2. Delay the onset of ignition.
     ⇒ Controlling combustion phasing.
     ⇒ For HCCI-like diesel, it allows more time for premixing before ignition.
  3. For gasoline HCCI, hot residuals are used to promote autoignition, and combined with cooled EGR, to control combustion phasing and NO_X.

- Although EGR is widely used, its thermodynamic and chemical effects on autoignition are only understood in general terms.

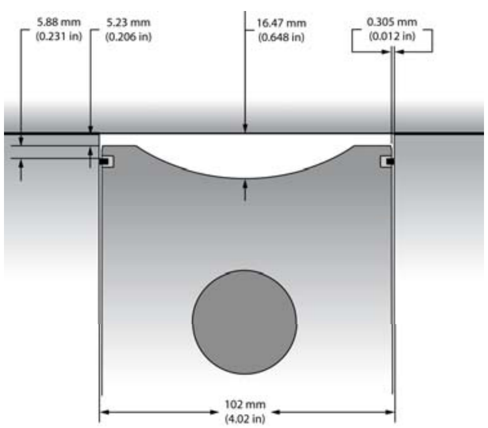
- **<u>Objective</u>:** Provide a fundamental understanding of how EGR and its constituents affect the autoignition of single- and two-stage ignition fuels.
  - Conduct well-controlled experiments in an HCCI engine.

HCCI Engine and Subsystems

Only premixed fueling is used for this study.



Cummins B
0.98 liter / cyl.



CR = 14 piston

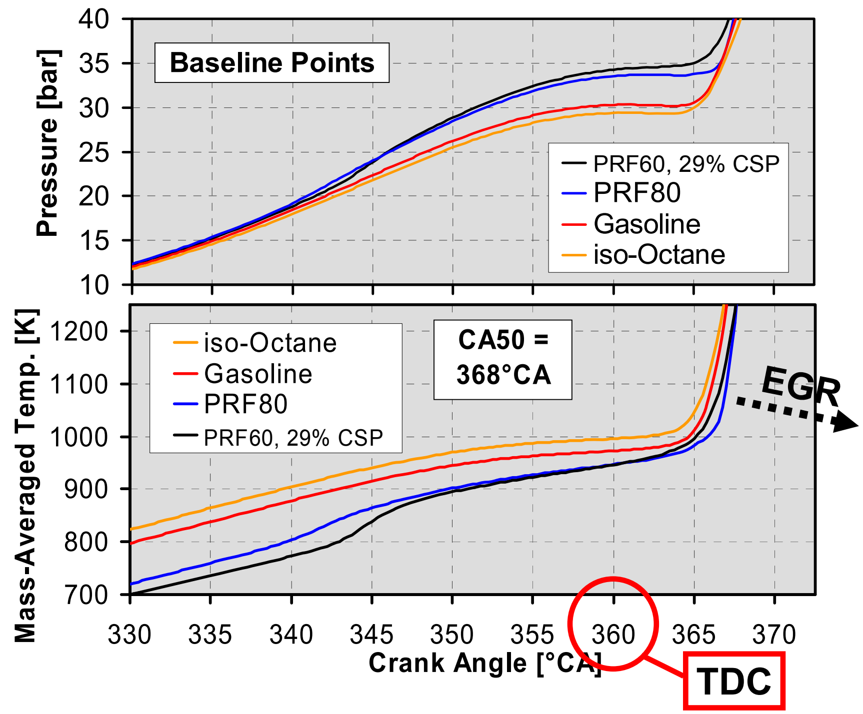
EGR Systems
- Real EGR
- Simulated EGR & EGR constituents

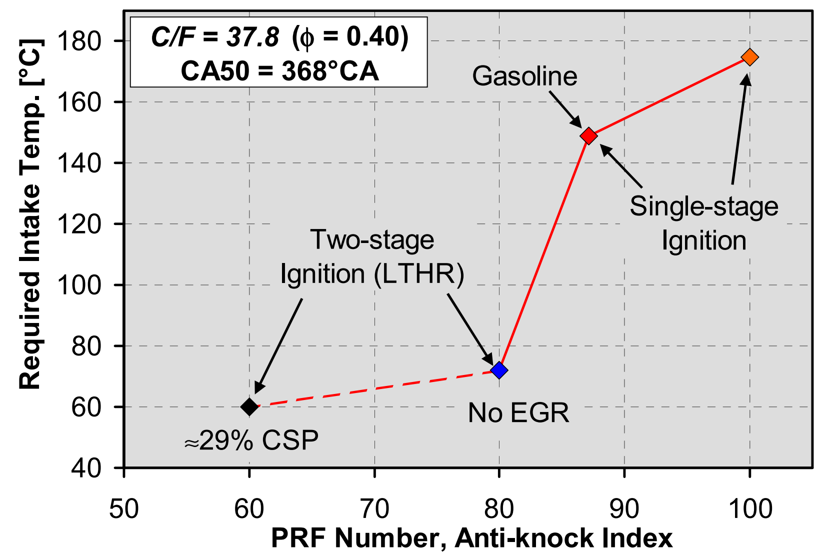
Baseline Points

- Establish baseline operating points for all four fuels.
  ➔ CA50 = 368°CA (8° aTDC)
- Study the retarding effects of EGR and its constituents.
- Iso-octane and gasoline exhibit single-stage autoig. at these conds.
- PRF80 and PRF60 have two-stage autoignition with LTHR.
  – Similar to diesel fuel (CN = 21 & 30).
- Baseline conditions have no EGR except for PRF60 ⇒ 29% CSP.

Operating Conditions

P_{in} = 100 kPa (naturally asp.)
1200 rpm.
C/F-mass ratio = 37.8,
(ϕ = 0.40 without EGR.)



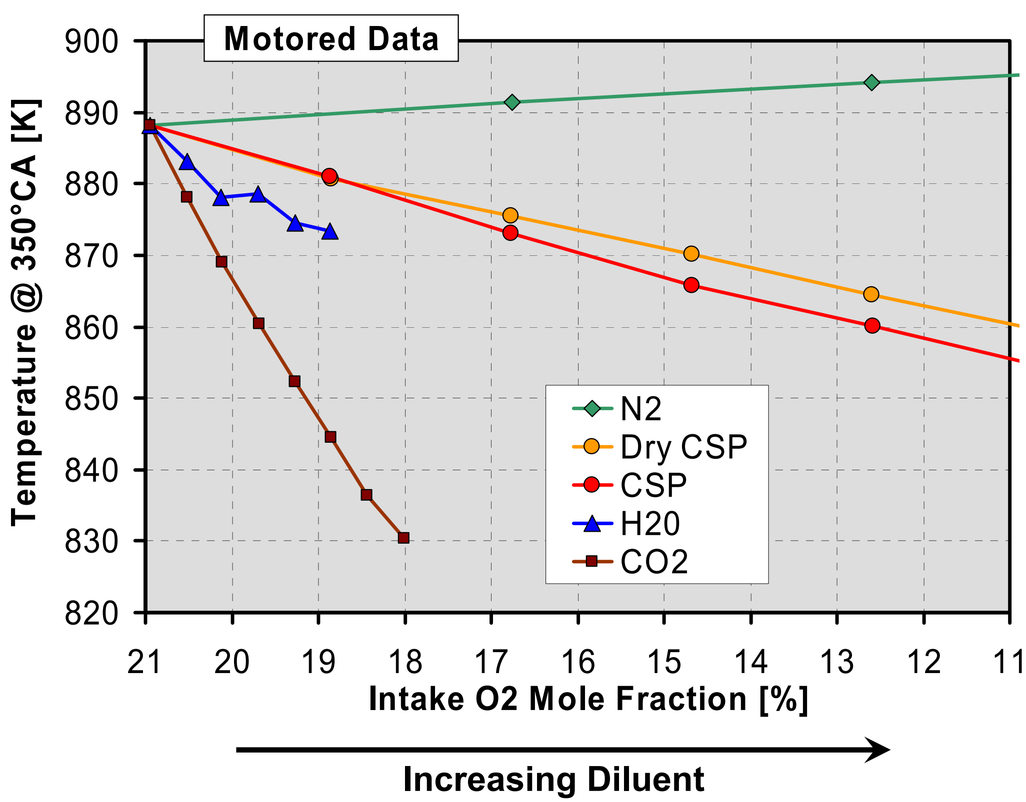


Composition of EGR (CSP)

- Consider complete combustion of iso-octane in "air".
  (Argon and atmospheric CO_2 lumped with N_2.)
- $C_8H_{18} + 12.5\ (O_2 + 3.773\ N_2) \Rightarrow 8\ CO_2 + 9\ H_2O + 47.16\ N_2$.
- For complete combustion with $\phi = 1$, the gas composition (excl. fuel) changes from air: **21% O_2 & 79% N_2** (mole basis).
- to: **12.5% CO_2, 14.0% H_2O and 73.5% N_2** for wet exhaust (CSP).
- to: **14.5% CO_2 and 85.5% N_2** for dry exhaust (Dry CSP).
- These gas compositions will be referred to as:
  Complete Stoichiometric Products ➔ **CSP** & **Dry CSP**.

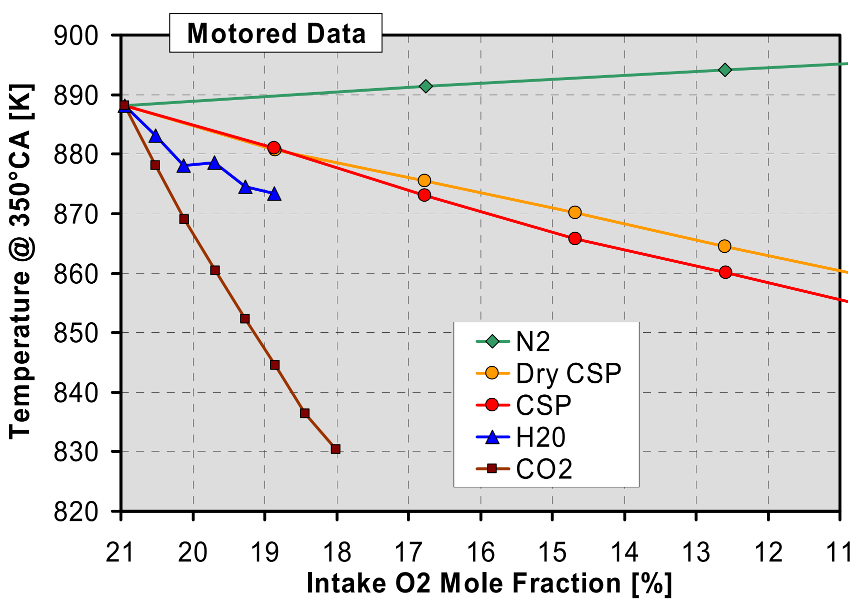
Thermodynamic Effects of EGR (CSP)

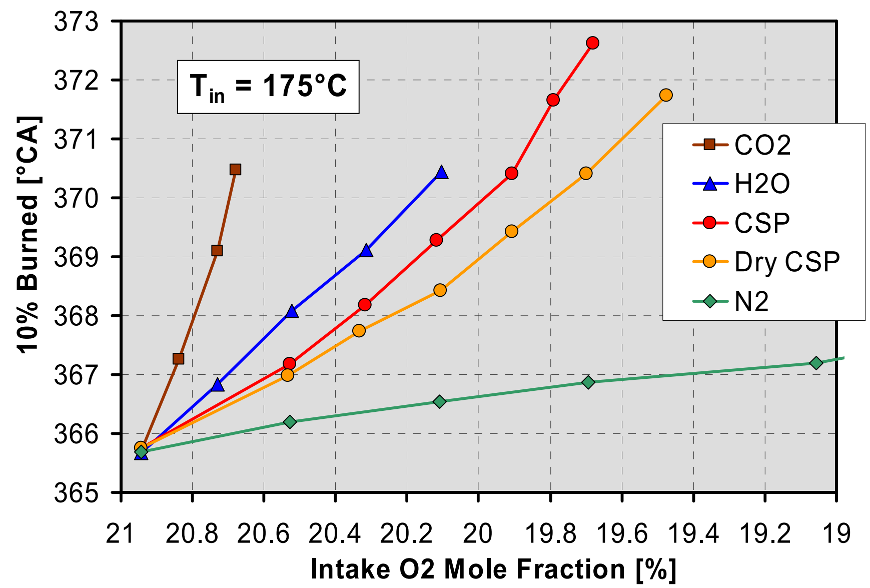
- EGR influences the compressed-gas temperature.
  - Heat-capacities of CSP & individual components are different from that of air.
- Start with motored operation. ⇒ Examine effects of CSP & its components on the mass-averaged temperature near TDC.
- Displace air while maintaining P_{in} = 100 kPa.
- Trends can be explained by changes in specific heat (C_v).
  - CO_2 has highest C_v (mole bs.).
  - H_2O high C_v.
  - N_2 ⇒ C_v slightly less than air.
  - CSP between air and H_2O.
  - Dry CSP slightly lower C_v than CSP.



Autoignition Retard for iso-Octane

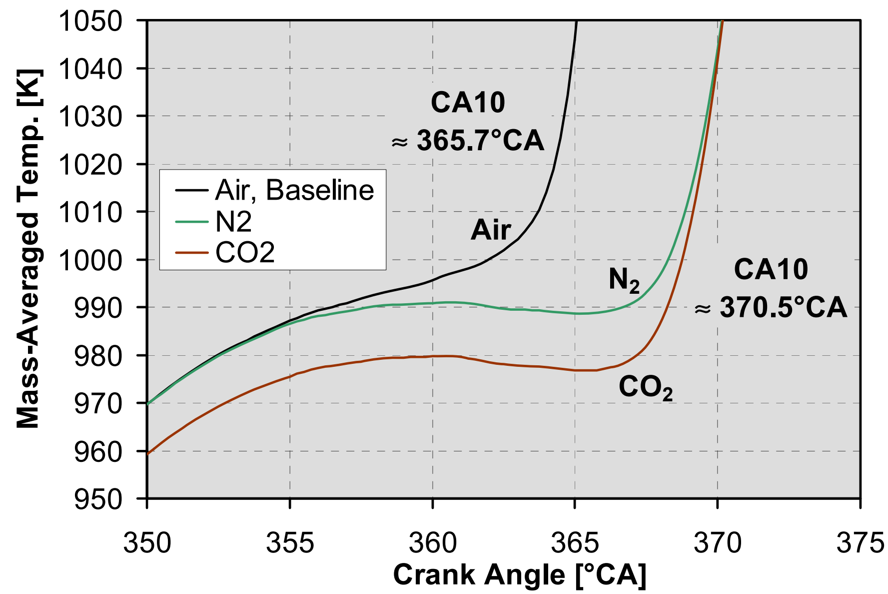
- Investigate the effect of these gases on combustion phasing.
- The autoignition retard is highly dependent on the type of the diluent.
- The retarding effect of the various gases is ordered consistently with their "cooling capacity" - **thermodynamic effect**.
- However, N_2 addition increases the compression temperature, but the phasing is retarded, so there must be a weak **chemical** [O_2] effect.

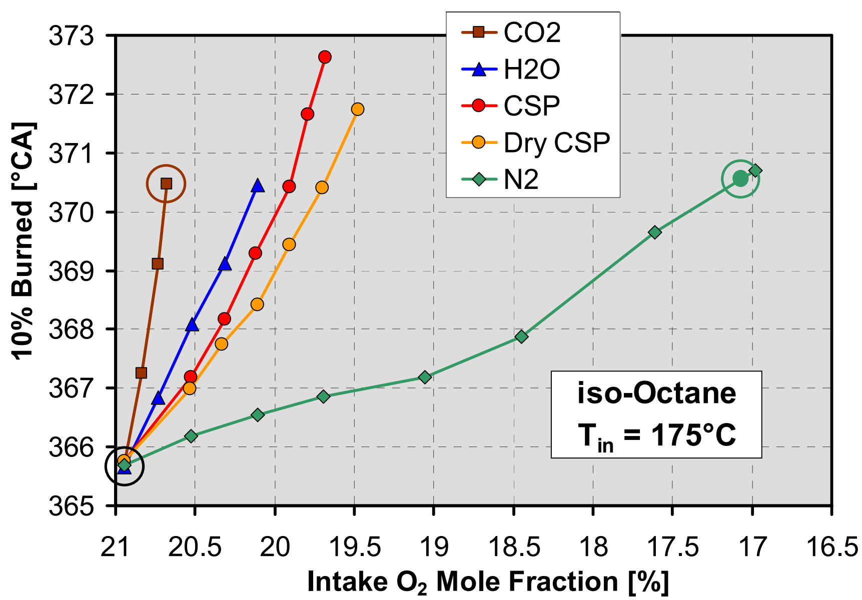


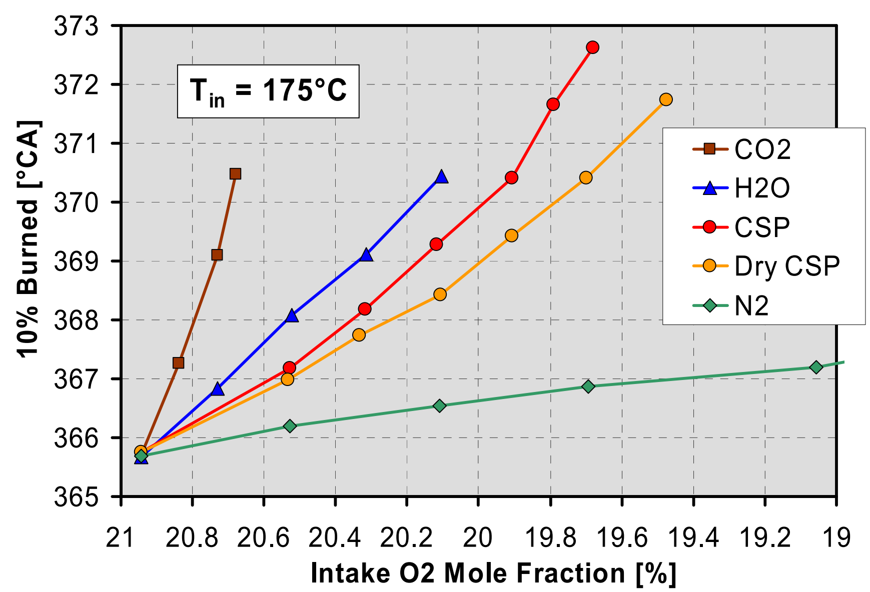


Temperature Traces for iso-Octane

- Retarding effect of lower [O_2] becomes more significant at higher levels of N_2 addition.
  - Clearly, reduction of [O_2] has to lead to misfire at some point.
- Temperature traces illustrate different mechanisms for retard.

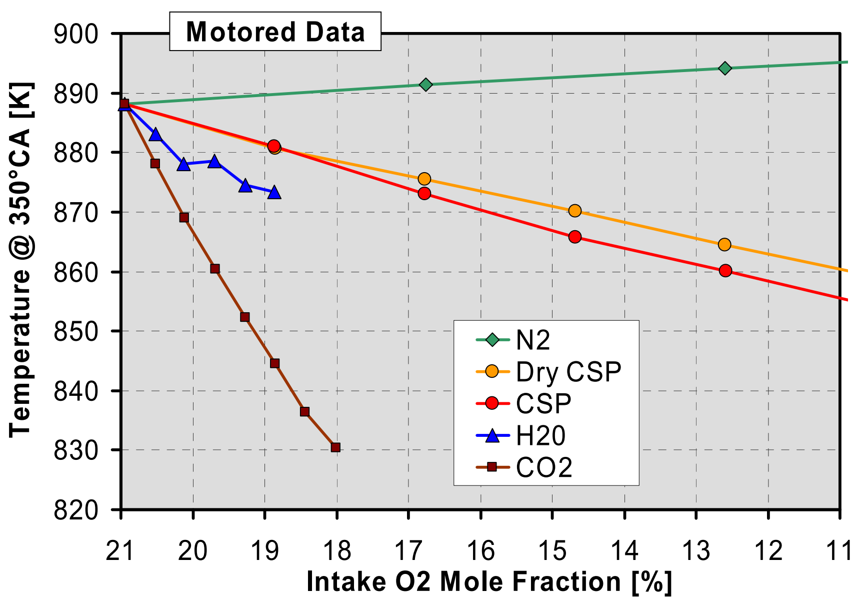


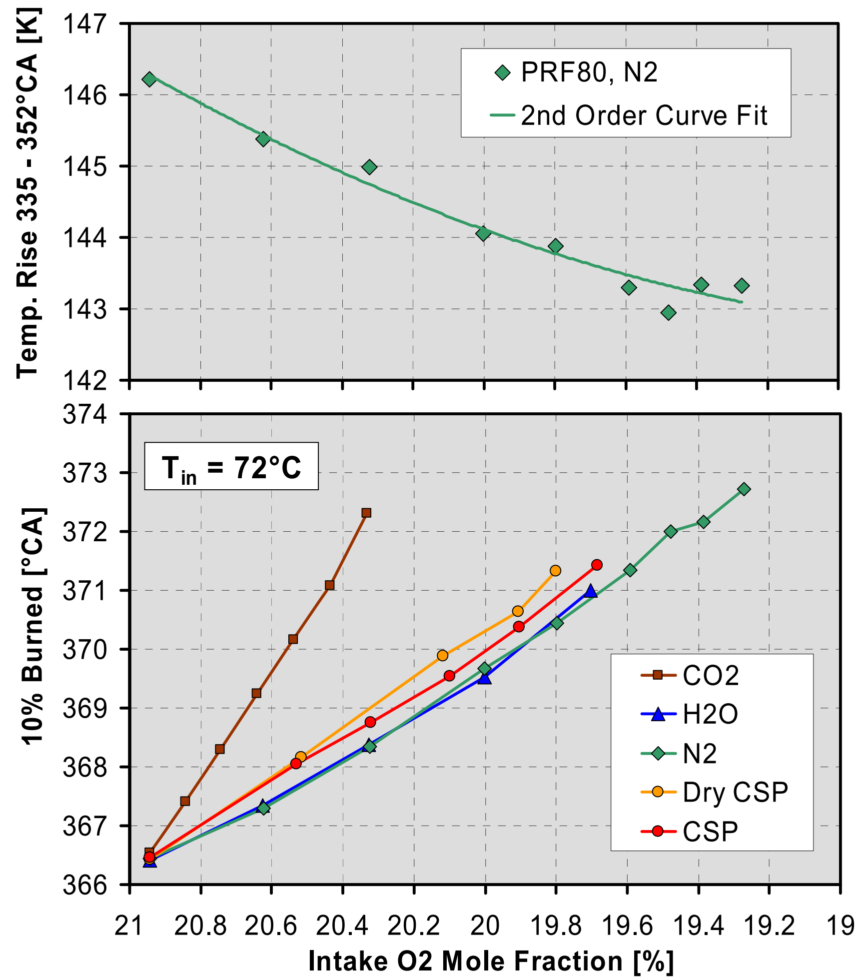




Autoignition Retard for PRF80 (2-Stage Ignition)

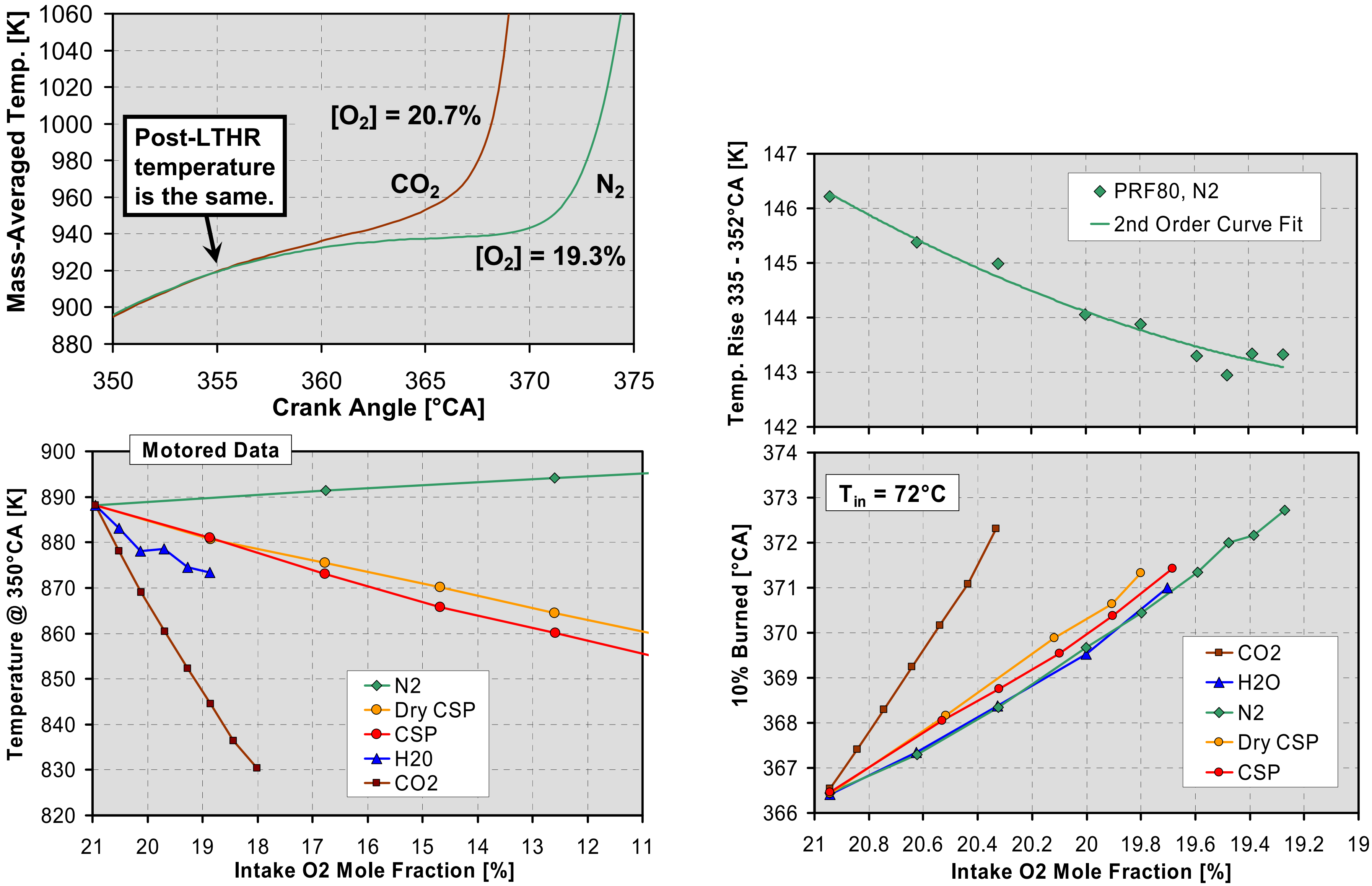
- For PRF80, the retarding effects are not consistent with the "cooling capacity" of the added gases (except for CO_2).
- N_2 addition (reduced [O_2]) strongly retards combustion phasing.
- PRF80's high sensitivity to [O_2] occurs for two reasons:
  - First, a reduced [O_2] reduces the LTHR.





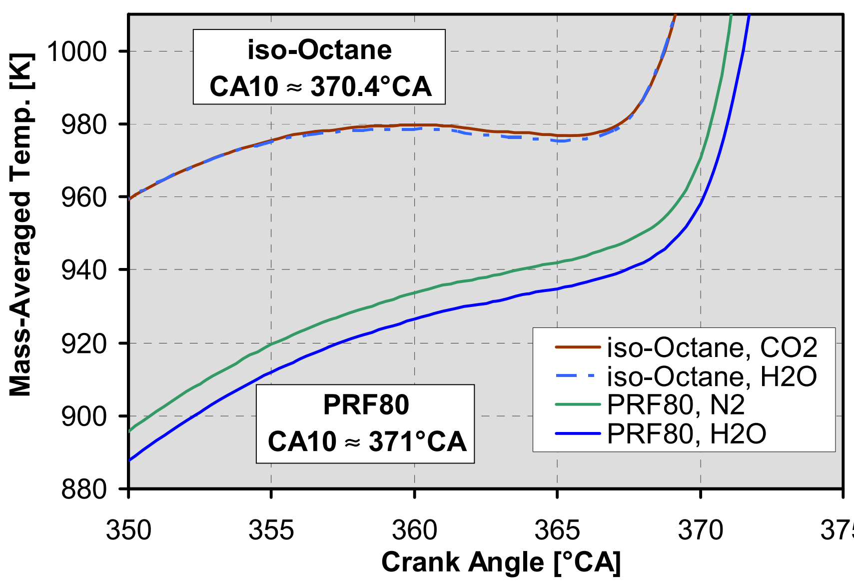
Autoignition Retard for PRF80 - [O_2]

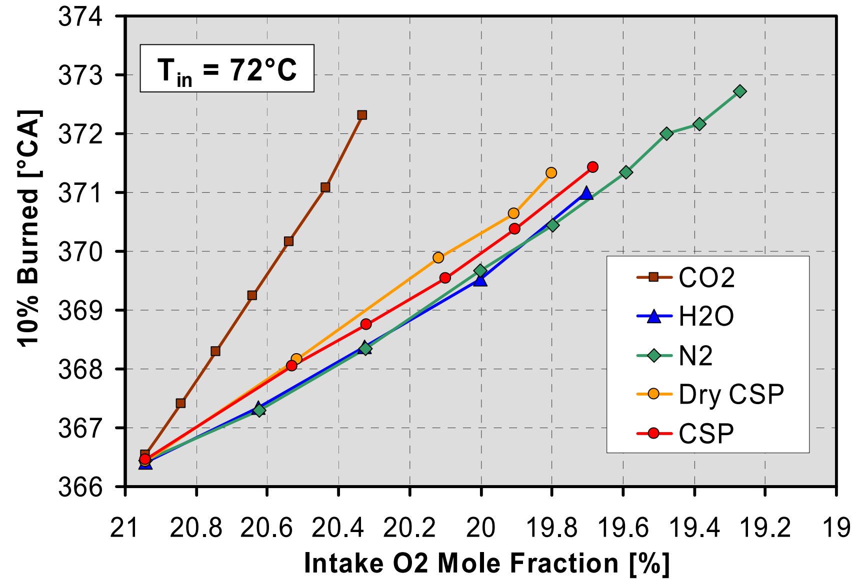
- Second, a reduced [O_2] also affects hot ignition.



All Constituents for PRF80 - H_2O

- Thermodynamic "cooling" should add to [O_2] effect for all constituents.
- Why is the retarding effect of H_2O equal to N_2?
- H_2O enhances the intermediate chemistry, so thermal run-away occurs at lower temperature.
  - Almost perfectly counteracts the cooling effect of H_2O!
- Also explains why CSP is less retarded than dry CSP.
- H_2O does not enhance the intermediate chemistry for iso-Octane.



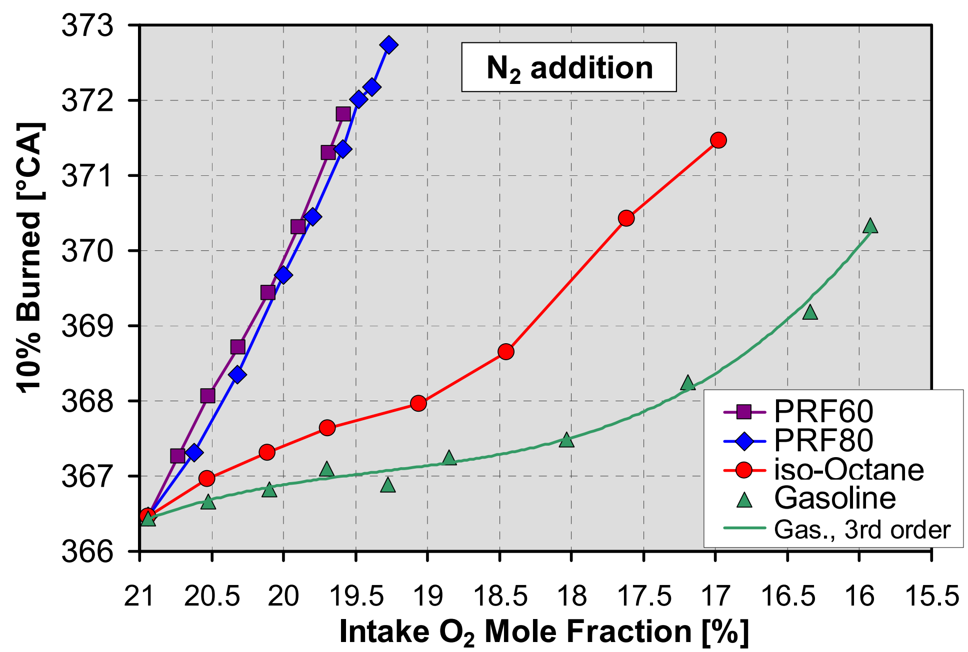


Comparing [O_2] Sensitivities

- Have now identified three mechanisms by which EGR affects phasing.

1. C_v effect (thermodynamic – retarding).
2. O_2-concentration effect (chemical – retarding).
3. H_2O effect (chemical – enhancing).

- Compare side by side for all fuels.
- N_2 addition gives most reduction in [O_2] for least change in C_v.
- The two-stage ignition fuels PRF80 and PRF60 are much more sensitive.
- Lower [O_2] both reduces LTHR and counteracts the hot ignition.
- Gasoline is initially very insensitive to [O_2].



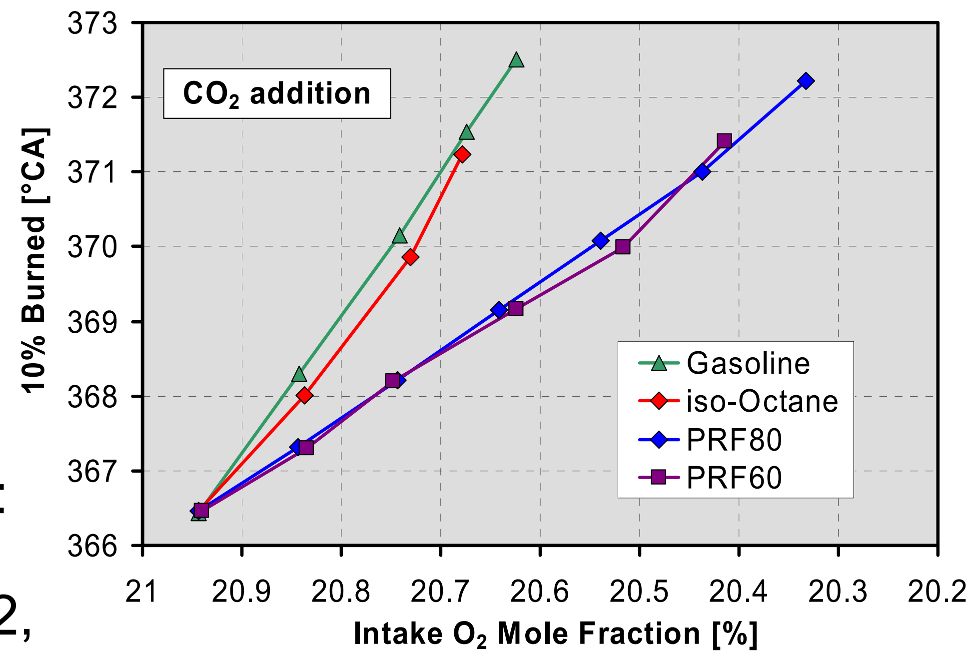
Comparing Thermal Sensitivities

1. C_v effect (thermodynamic – retarding).

2. O_2-concentration effect (chemical – retarding).

3. H_2O effect (chemical – enhancing).

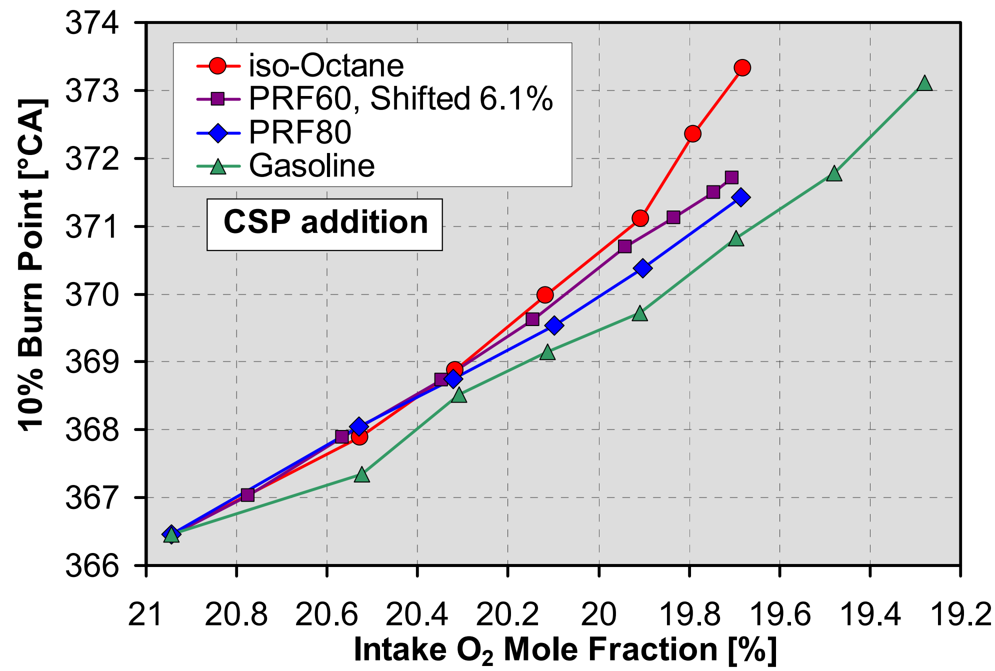
- CO_2 addition gives most thermodynamic cooling, with least change in $[O_2]$.
- The single-stage ignition fuels, iso-octane and gasoline, are much more sensitive to the cooling effect of CO_2.
- The reason for this explained in: *Proceedings of the Combustion Institute*, Vol. 31, pp. 2895–2902, 2007.



Comparing CSP Effects

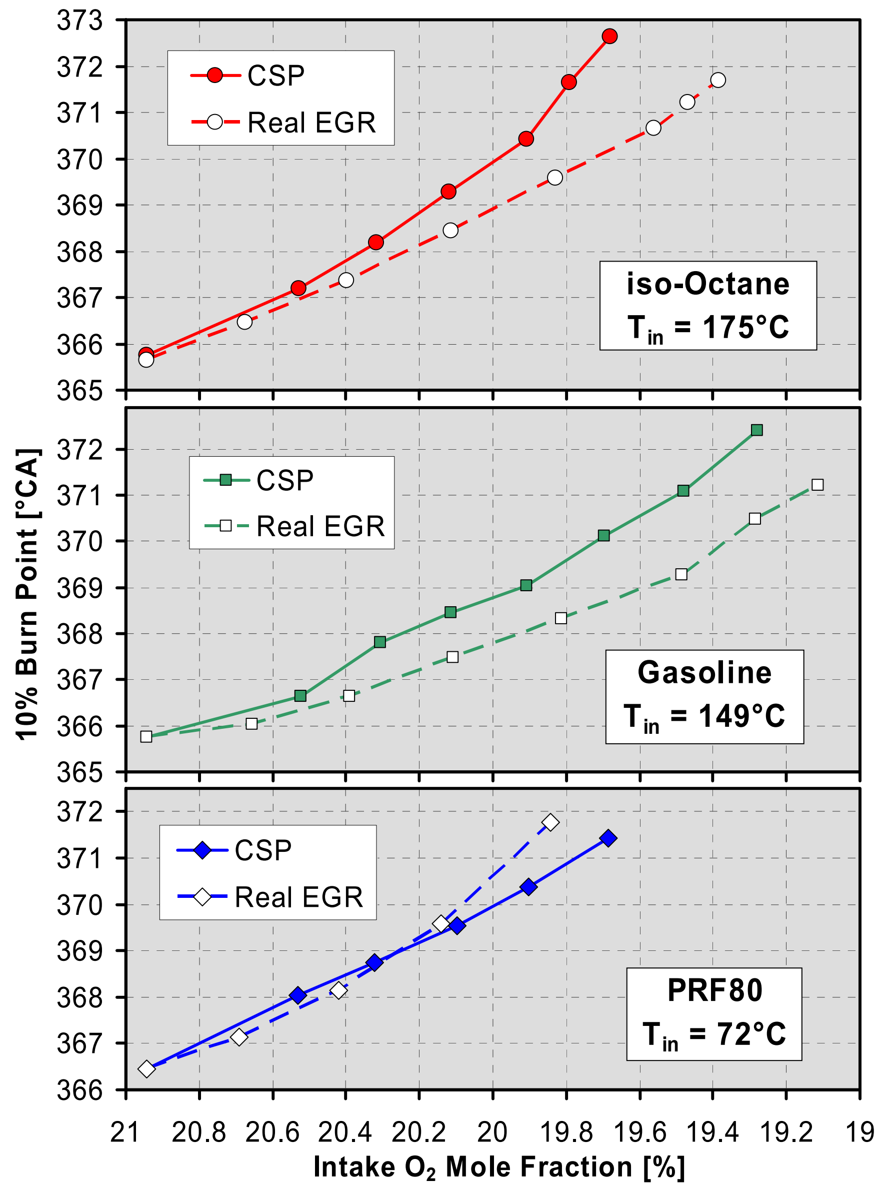
1. C_v effect (thermodynamic – retarding).
2. O_2-concentration effect (chemical – retarding).
3. H_2O effect (chemical – enhancing).

- The overall effect of CSP results from the combination of these three mechanisms.
- CSP gives similar amounts of retard for all four fuels.
- But underlying mechanisms are different.
- Trace species in real EGR add to these effects.



Real EGR Effects

- Real EGR contains trace species that also affect the autoignition.
  - Unburned fuel, partially oxidized fuel, formaldehyde, CO, and other species.
- For iso-Octane and Gasoline, real EGR retards less than CSP.
- For PRF80, real EGR has a retards slightly more than CSP.
- The net effect of these species is to advance the ignition for iso-octane and gasoline...
- ...but to retard it for PRF80.



Summary / Conclusions

- EGR is very effective for suppressing autoignition reactivity.
  - Can be used beneficially for controlling combustion phasing across load and speed ranges.

		Iso-Octane, Gasoline	PRF80, PRF60
±	***Effect:***	**Single-stage**	**Two-stage with LTHR**
Retarding	***C_v effect (thermodynamic)***	**Strong**	**Weak**
	[O_2] effect (chemical)	**Weak**	**Strong**
Enhancing	***H_2O effect (chemical)***	**None to weak**	**Strong**
	Trace Species	**Moderate enhancing**	**Moderate retarding**

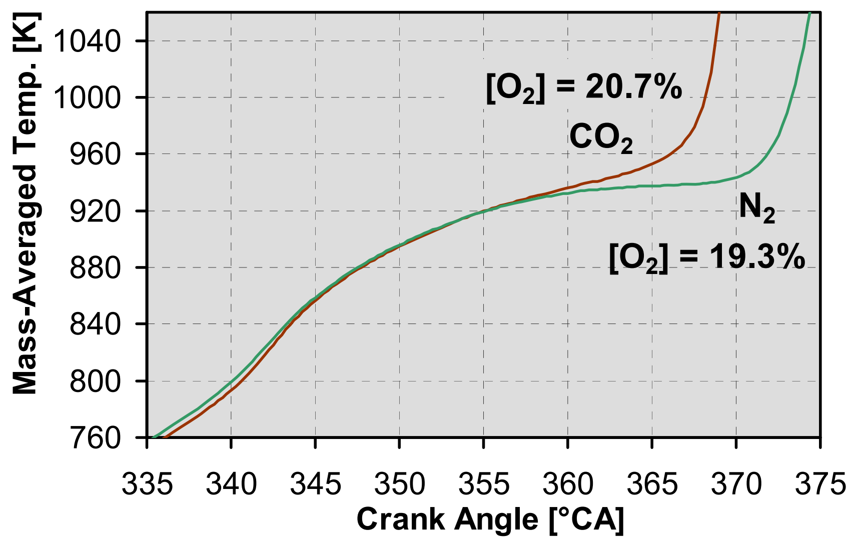
- The net result of the different thermal, O_2, and H_2O sensitivities is a fairly similar effect of CSP for all fuels.
- Trace species (unburned and partially oxidized fuel, and CO) influence the effect of real EGR.

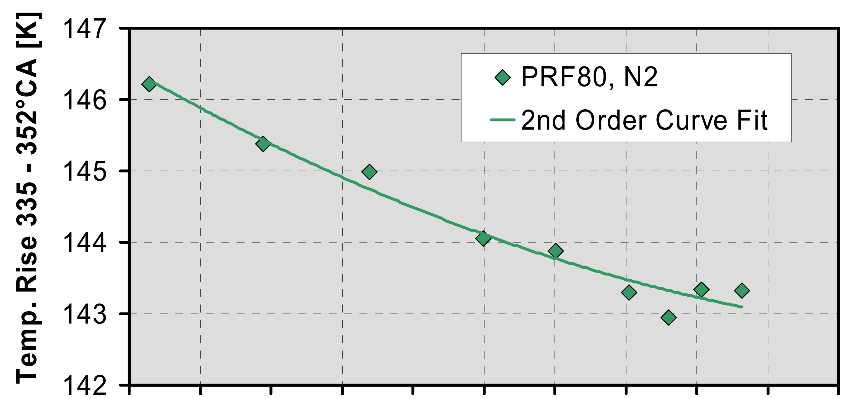
Details in: SAE 2007-01-0207

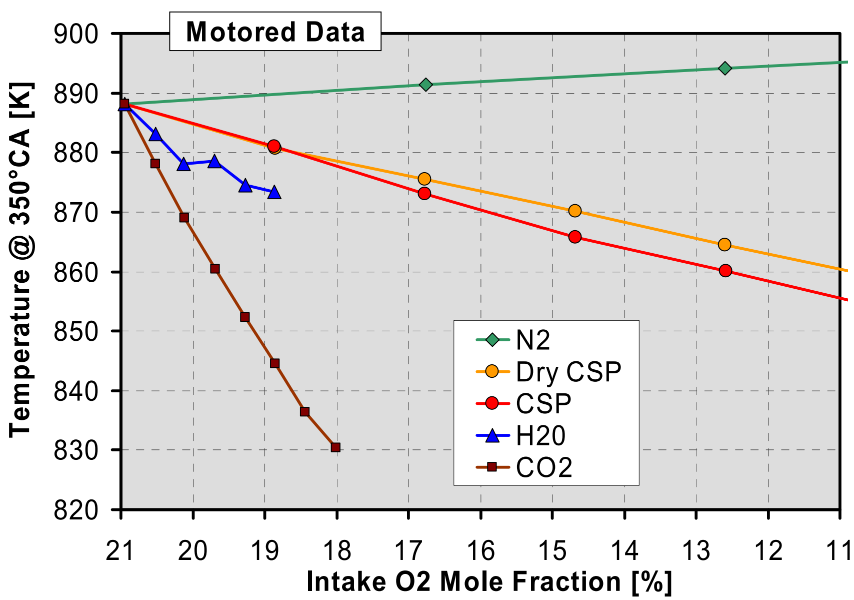
End Presentation

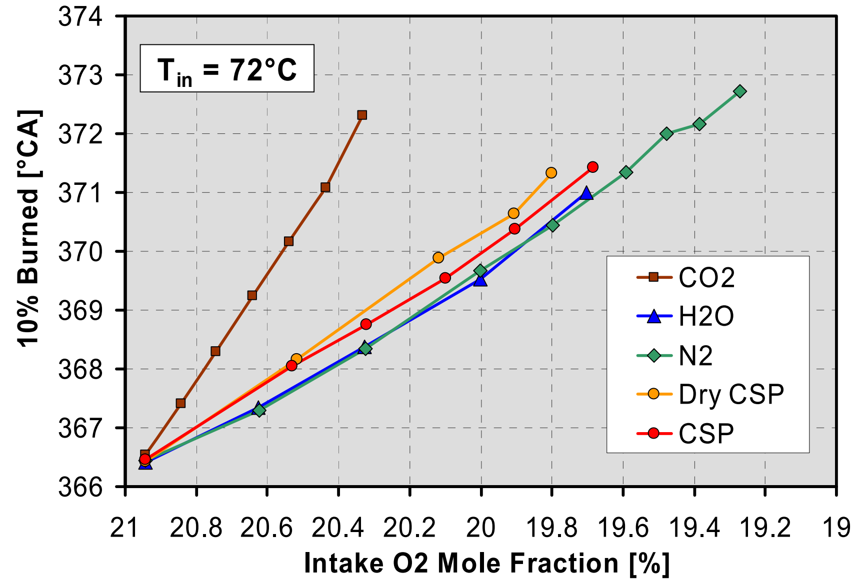
Autoignition Retard for PRF80 - [O_2]

- Lower [O_2] also affects hot ignition, in addition to reducing the LTHR.



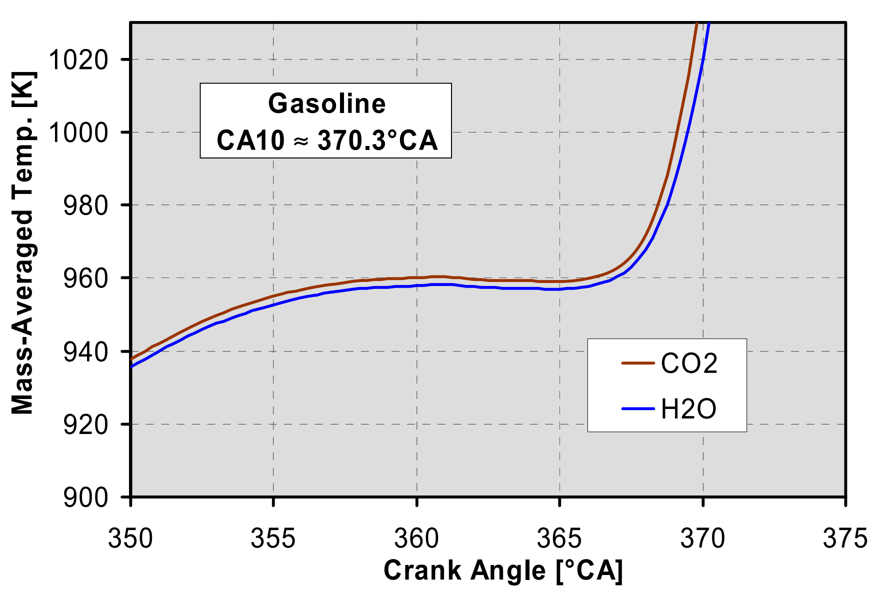


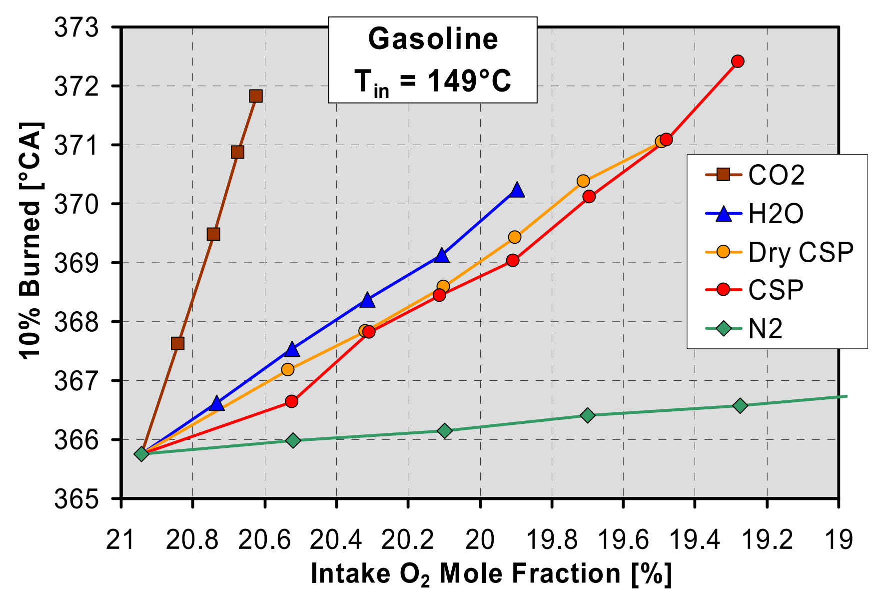




Autoignition Retard for Gasoline

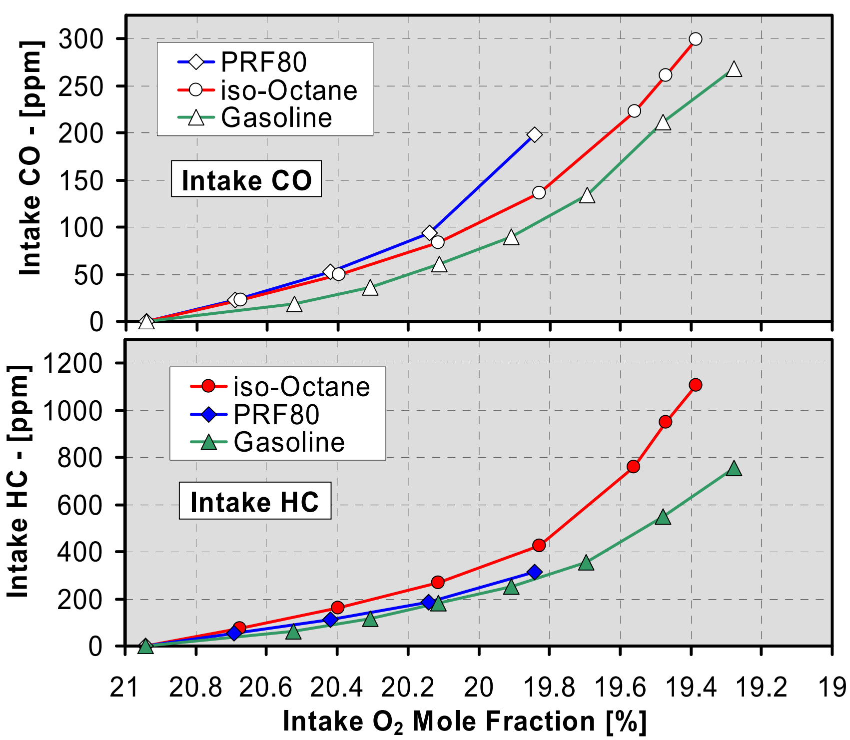
- N_2 addition shows that the chemical $[O_2]$ effect is very weak.
- Retarding effect of H_2O is weaker than expected based on its high C_v.
- CSP (with water) has a slightly weaker retarding effect than dry CSP.
- Temperature traces confirm that H_2O has an enhancing effect on autoignition for gasoline.
- Effect is stronger than for iso-octane, but much weaker than for PRF80.

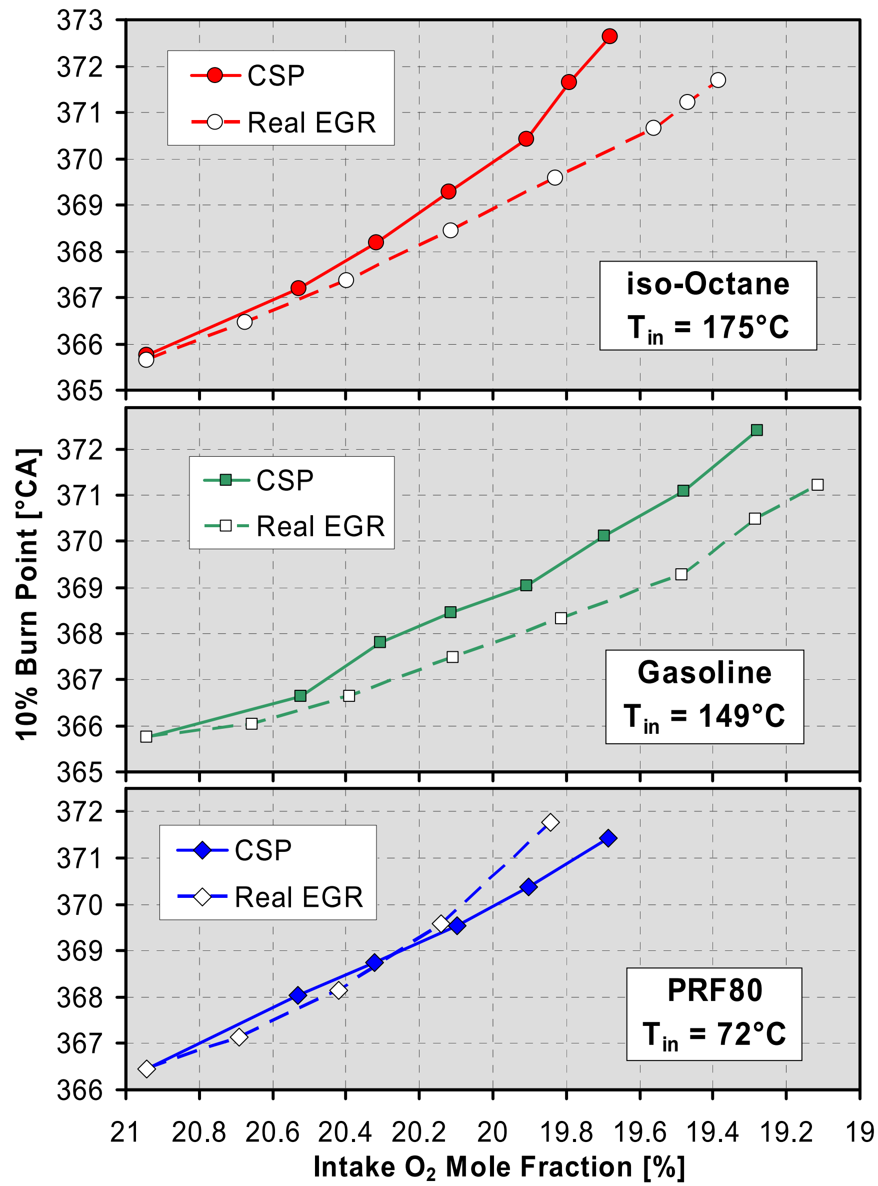




Real EGR Effects (2)

- Intake concentrations increase with EGR level and retard.
- These effects of Real EGR are also important for explaining the effects of retained residuals.
- Discussed in *Proceedings of the Combustion Institute*, Vol. 31, pp. 2895–2902, 2007.





Compare with NIST Database

- All air displacement except N_2 reduce the compression temperature.
- Can be explained by changes of the specific heat capacity.
- CO_2 has **highest** specific heat capacity on a mole basis.
- H_2O has **high** specific heat capacity.
- N_2 has slightly lower specific heat capacity compared to air.
- CSP falls between Air and H_2O.
- Dry CSP has slightly lower C_v compared to CSP.