SAND2015-3001C

Efficiency Benefits of Lean or Dilute Well-mixed DISI Engine Operation with Advanced Ignition, Intake Heating and Various Fuel Types

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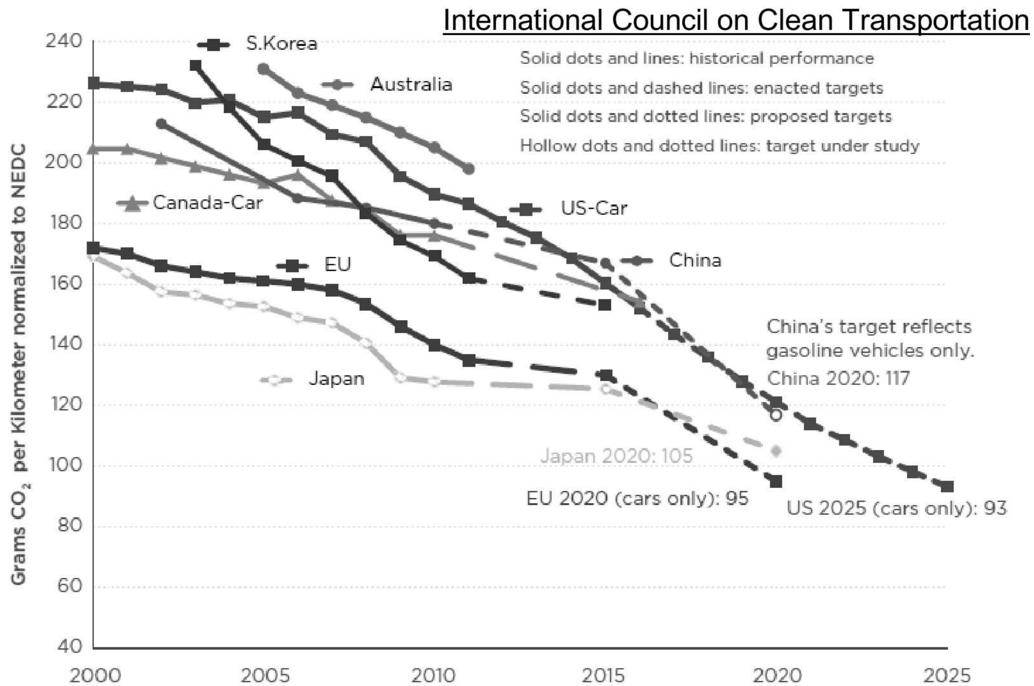
SAE 2015 High Efficiency IC Engine Symposium
April 19-20, 2015

Acknowledgement

The work was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Financial support was provided by the U.S. Department of Energy, Office of Vehicle Technologies. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Introduction

- Strong pressure to reduce CO_2 emissions.
- Improved engine efficiency is one key factor.
- Stoichiometric SI operation is standard for gasoline-type engines.
- **Lean and/or dilute SI operation** can improve fuel economy.



- Combustion stability is one key issue.
- World-wide mandates for renewable fuels.
- Motivate examination of **ethanol fuel blends** for advanced combustion.

Technical Scope

- Fuels: Gasoline, E30 and E85
- Fuel/air-mixing states:
  - Well-mixed charge.
- Ignition methods:
  - Regular high-energy inductive spark system (106 mJ electrical).
  - Multi-pulse (MP) transient plasma (16mJ electrical).
- Dilution types & fuel/air ratio:
  - Excess air. $\phi \leq 1$
  - Simulated EGR using N_2. $\phi = 1$, stoichiometric conditions.
- Combustion modes:
  - Deflagration.
  - Deflagration $\Rightarrow$ end-gas autoignition.

Objectives

- Examine selected data sets to identify opportunities for improved thermal efficiency relative to that of traditional stoichiometric operation.

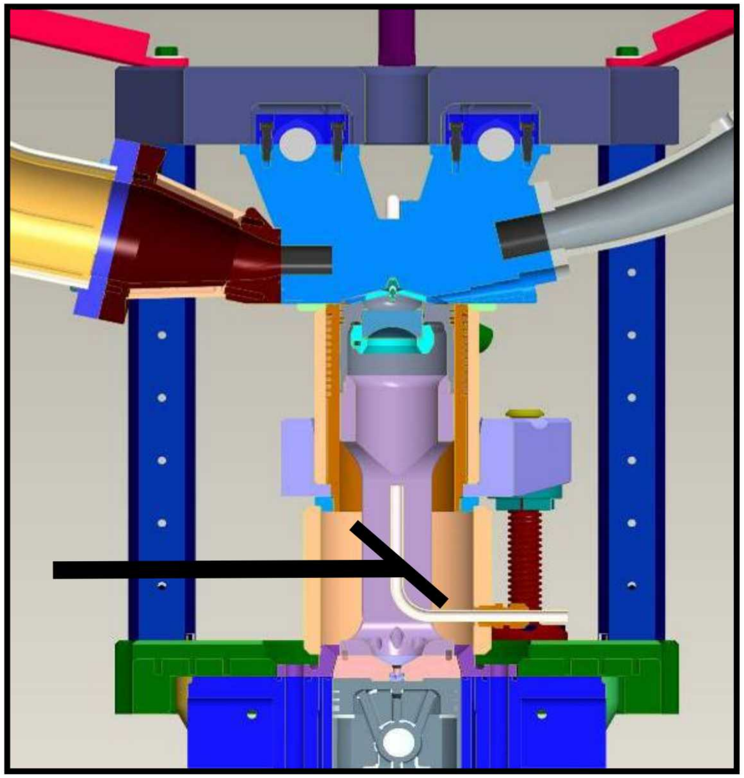
A. Lean well-mixed SI operation using regular spark.
   - Gasoline & E85: Fuel effects?
   - Enabling factors:
     - Intake charge heating.
     - Mixed-mode combustion (deflagration $\Rightarrow$ autoignition)
   - Limitations:
     - Combustion variability.
     - Combustion inefficiency.
     - Lack of combustion-phasing control.
   - NO_x emissions / dilute operation.

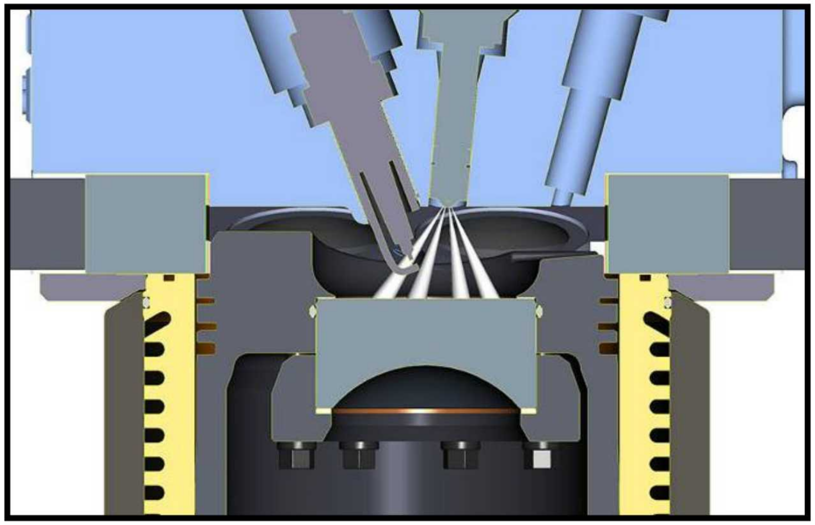
B. Opportunities with enhanced ignition.
   - Multi-pulse (MP) transient plasma.
   - Quantify control authority.

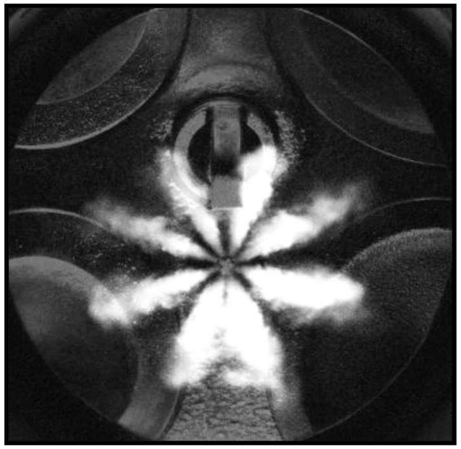
- Combine:
  - All-metal performance testing with emissions measurements.
  - High-speed imaging of spray, ignition and flame development.

Research Engine

- Drop-down single-cylinder engine.
- Automotive size. 0.55 liter swept volume.
- Identical geometry for **All-metal** and **Optical.**
- Designed for spray-guided stratified-charge operation $\Rightarrow$ Piston bowl.
- Injections during intake stroke $\Rightarrow$ well-mixed charge.

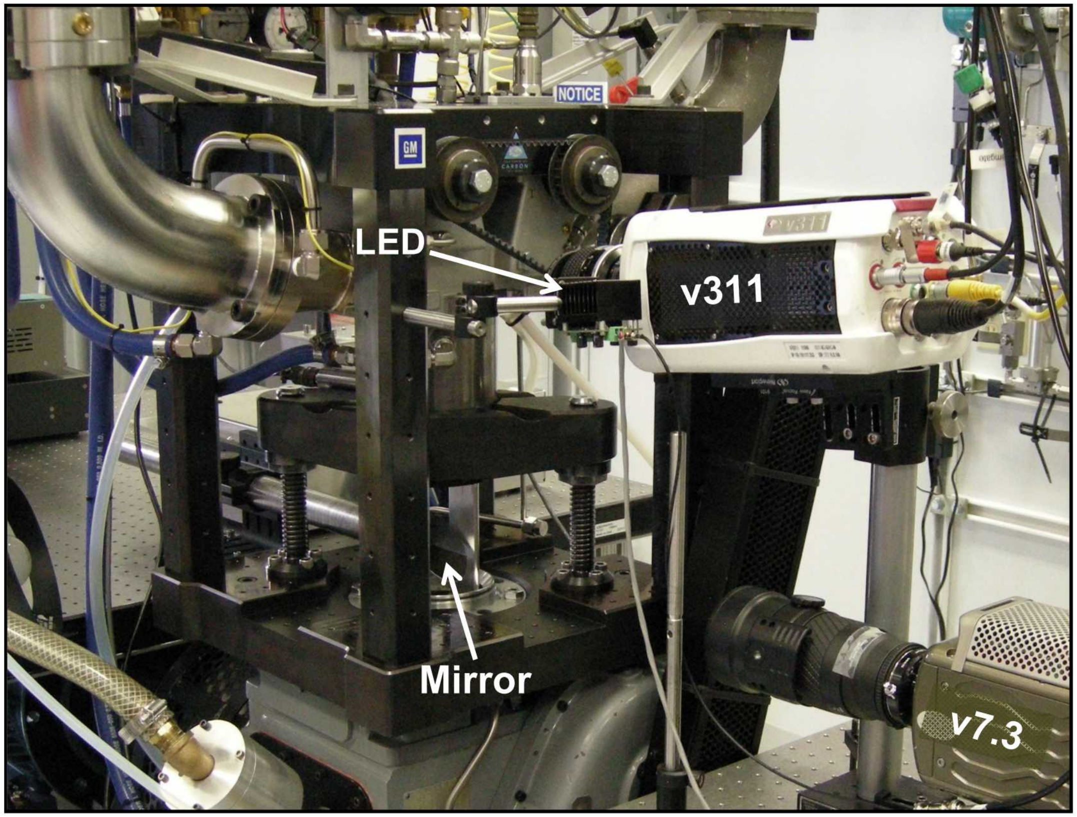


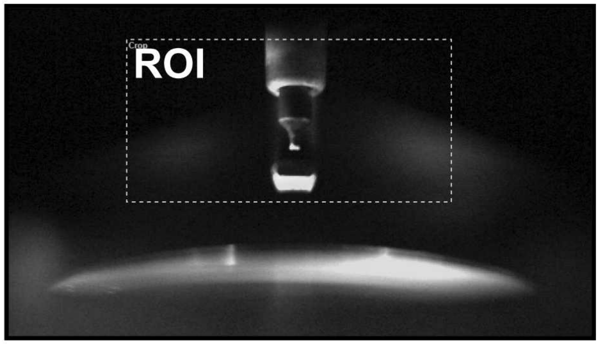


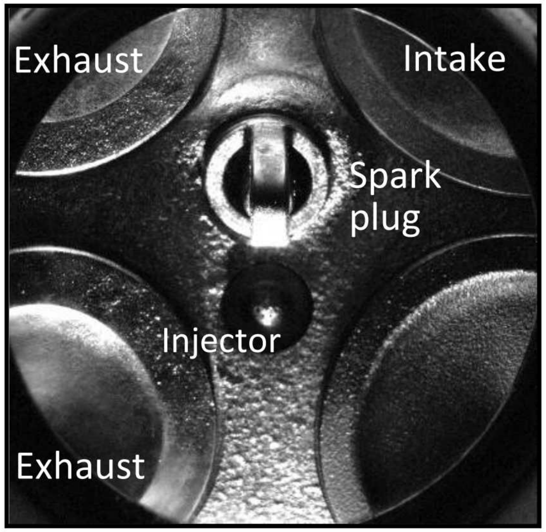


Imaging Setup

- High-speed imaging: 20 kHz.
- Phantom v7.3 & v311, monochrome.

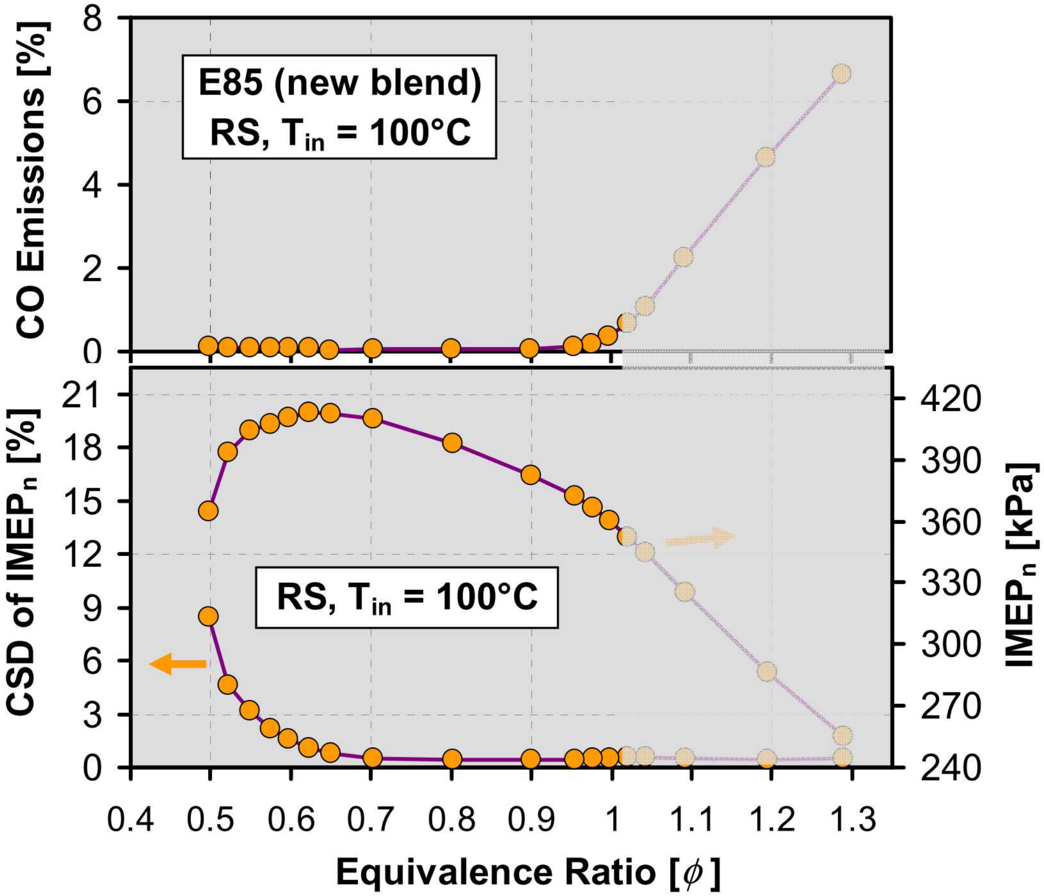






Operating Conditions

- Constant fuel mass ⇒ $IMEP_n$ reveals efficiency changes.
- Focus on lean combustion.



Parameter	This Data Set
Fuel Type	E85
Engine Speed	1000 rpm
Fuel per Cycle	21.6 mg
Intake Pressure	39 - 88 kPa
Target CA50	5°CA

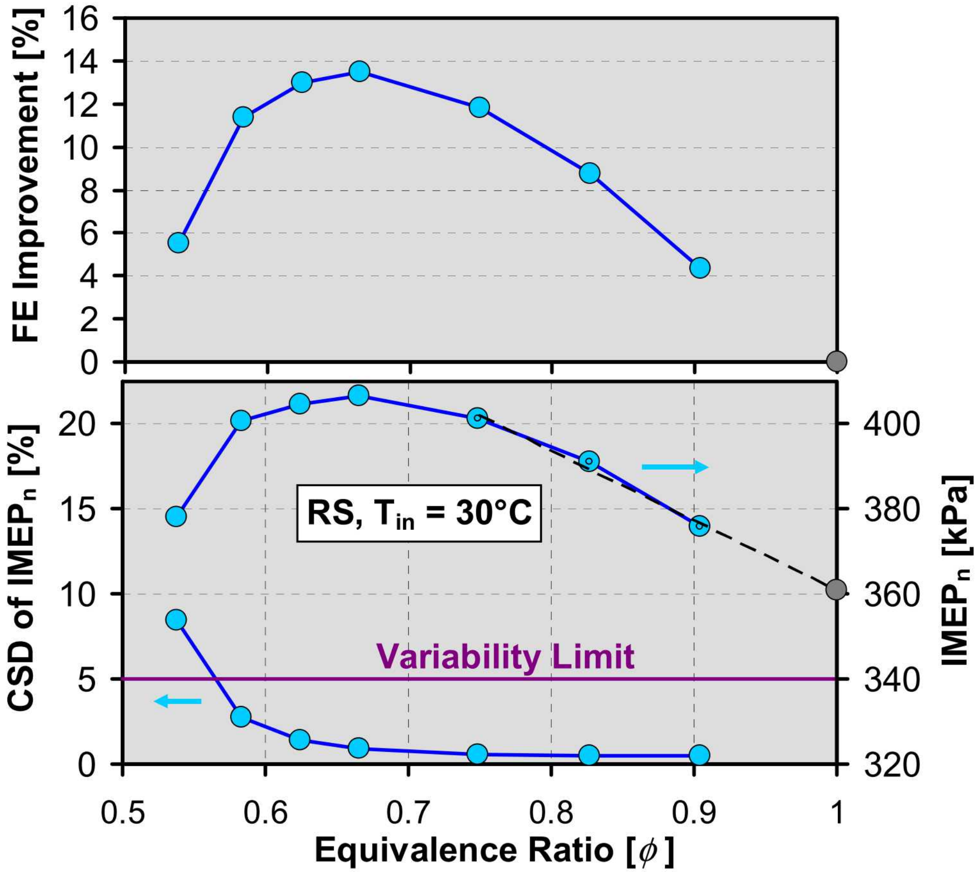
Parameter Space

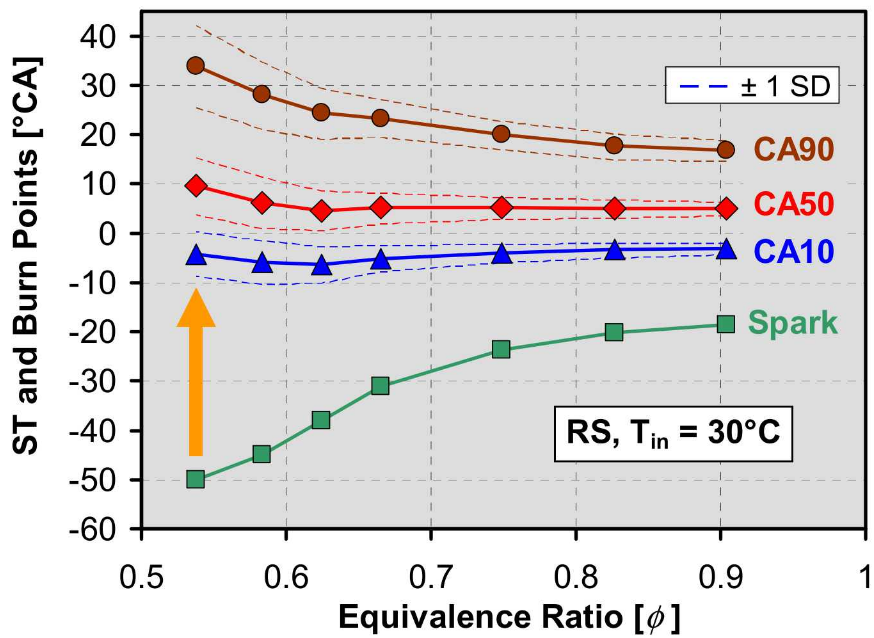
- Grouped as hardware, static parameters & operating variables.
- Low residual gas level, 4 – 6% by mass.
- Fuel mass adjusted to $IMEP_n$ = 360 – 370 kPa for $\phi = 1$ operation.

Parameter	This Presentation
CR	12
Piston Bowl	∅ 46 mm
Valve Timings	For Minimal Residual Level
Injector & Spray Targeting	Bosch 8 x 60° Straddling Spark
Swirl Index	2.7
Tumble Index	0.62
Engine Speed	1000 rpm
Injection Pressure	170 bar
$P_{exhaust}$	100 kPa
$T_{coolant}$	75°C
$IMEP_n$, $\phi = 1$	360-370 kPa
Fuel Type	Gasoline, E30, E85
Fuel Mass	15.6,17.8, or 21.6mg
ϕ	1.3 - 0.44
Intake Pressure	37 – 96 (107) kPa
T_{in}	30°C or 100°C
EGR / $[O_2]_{in}$	11.9 - 21% O_2

ϕ - Sweep, E85, Regular Spark (RS)

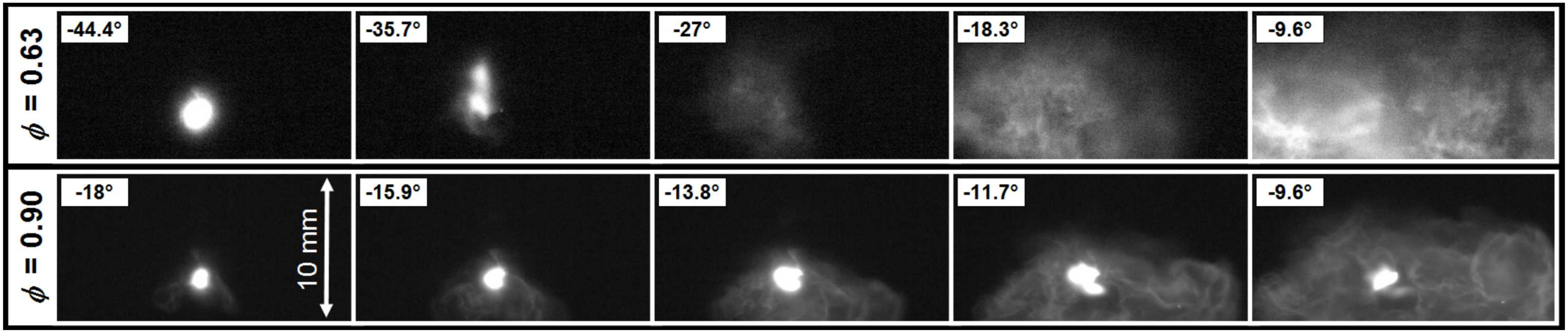
- $IMEP_n$ increases by 13% at $\phi = 0.67$.
- Lower $\phi \Rightarrow$ Unacceptable $IMEP_n$ variability.
- Spark – CA10 induction period becomes excessive.





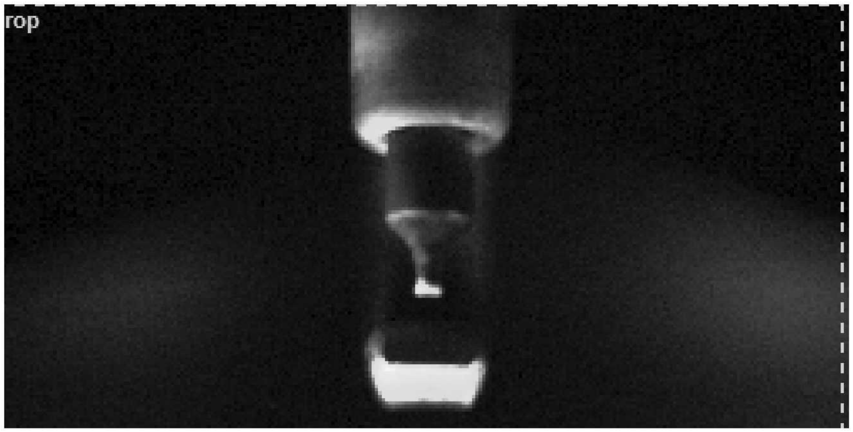
High-Speed Imaging, E85 Regular Spark

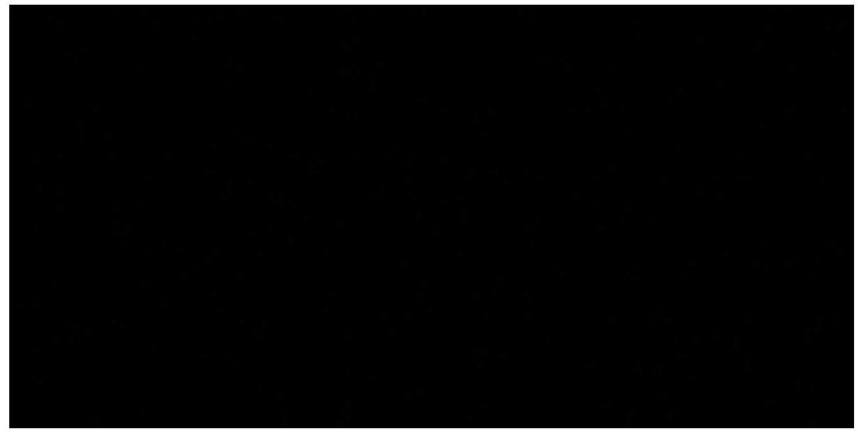
- Lean operation ⇒ fragile flame kernel.



Spark Discharge Variations

- Flow field has cycle-to-cycle variability.
- Evidenced by plasma-channel variations.

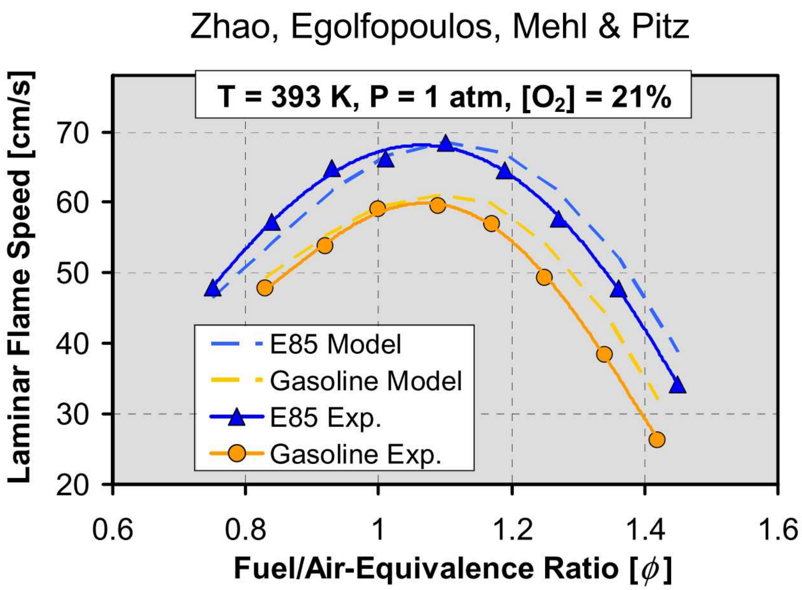


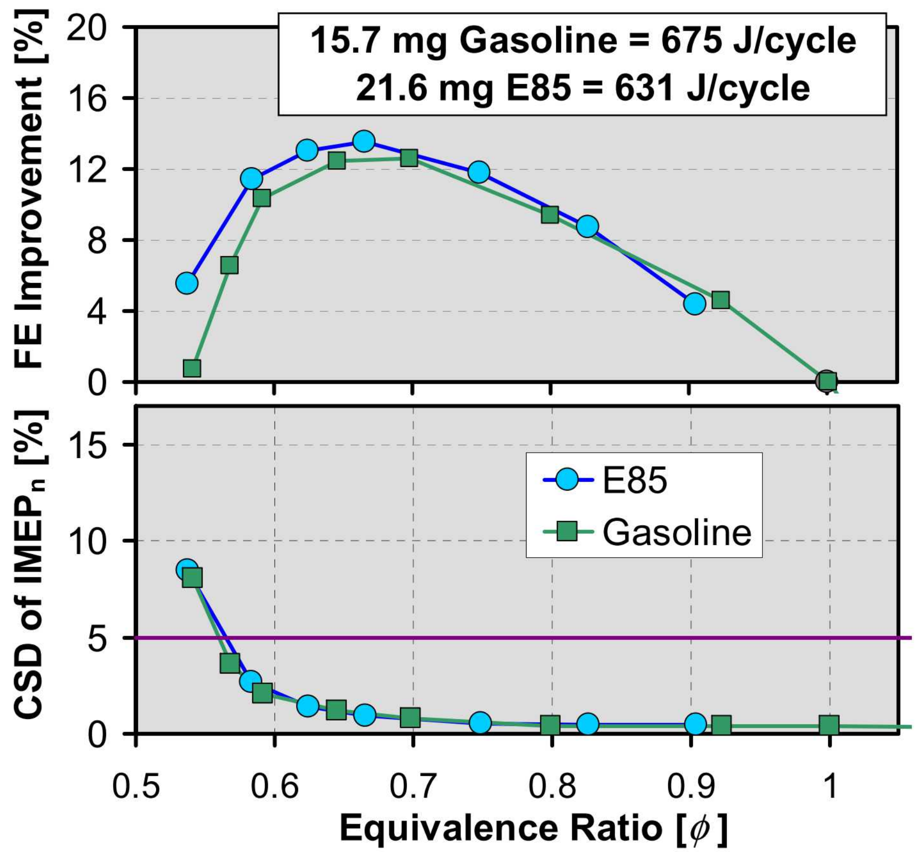


- Contributes to cycle-to-cycle variability for lean operation.
  - Fragile flame kernel.
  - Long induction time from spark to CA10.

ϕ - Sweeps, Regular Spark, E85 and Gasoline

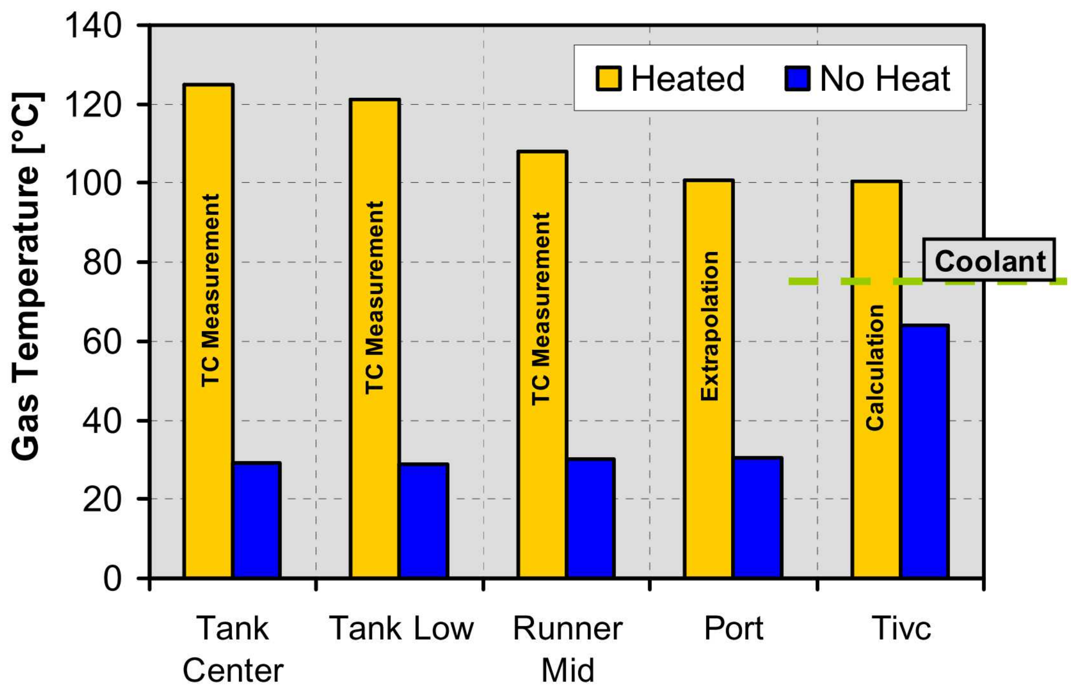
- $T_{in} \approx 30°C$. Identical lean instability limits for gasoline and E85.
- Flame measurements and modeling suggest stronger E85 flame.
- Recent modeling by Marco Mehl at LLNL shows that flame speeds of early flames for gasoline and E85 become nearly identically low for $\phi < 0.6$.
- Also possible that stronger DI vaporization cooling effect of E85 counteracts a slightly stronger E85 flame.
- FE gains are similar for gasoline and E85.

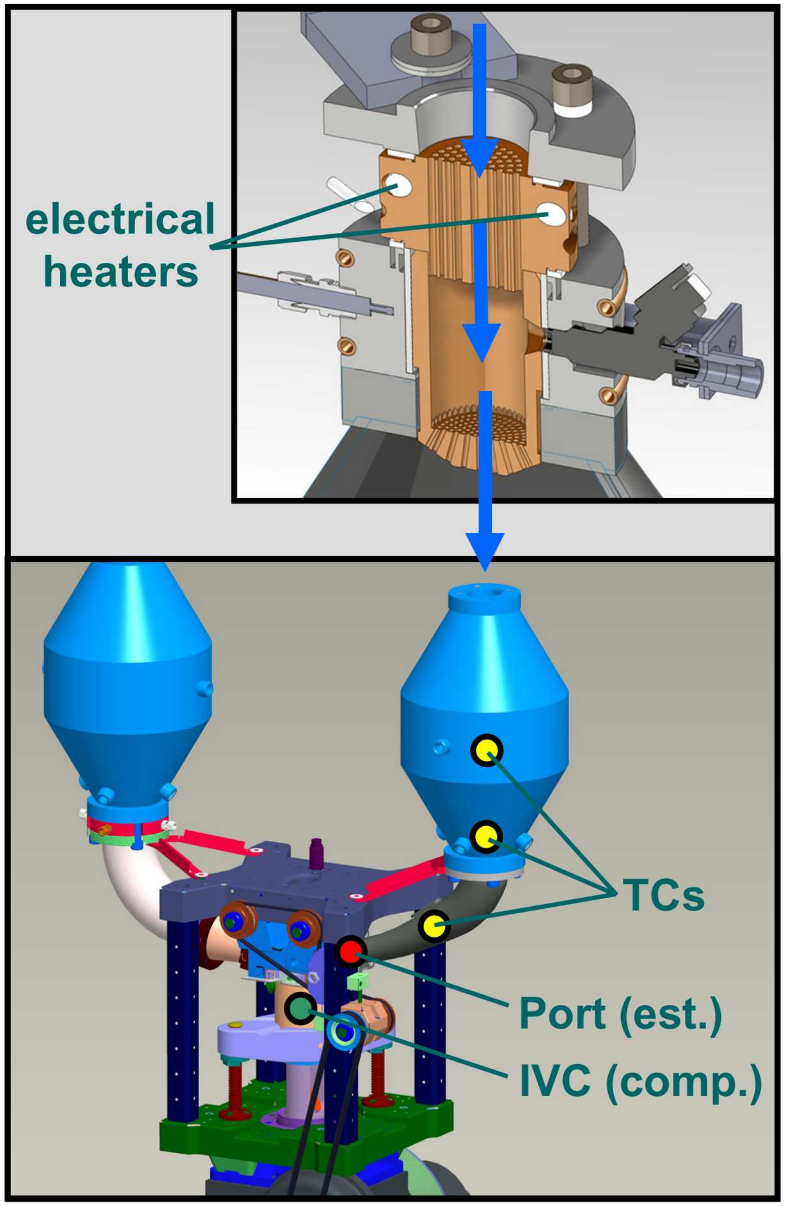




Intake Air Heating

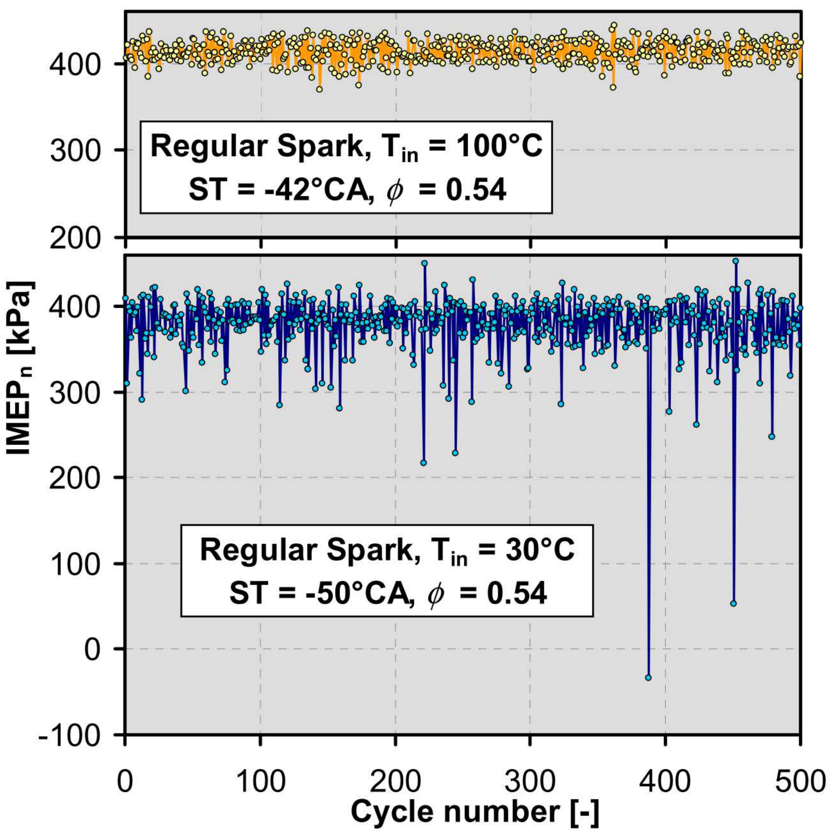
- Electrical intake air heater.
- Three thermocouples ⇒
- Estimate port temp. Rises 70 K.
- Also, compute T_{IVC}. Rises only ≈40 K.
  - Heat-transfer during intake stroke.
  - Mixing with residuals (≈5%).

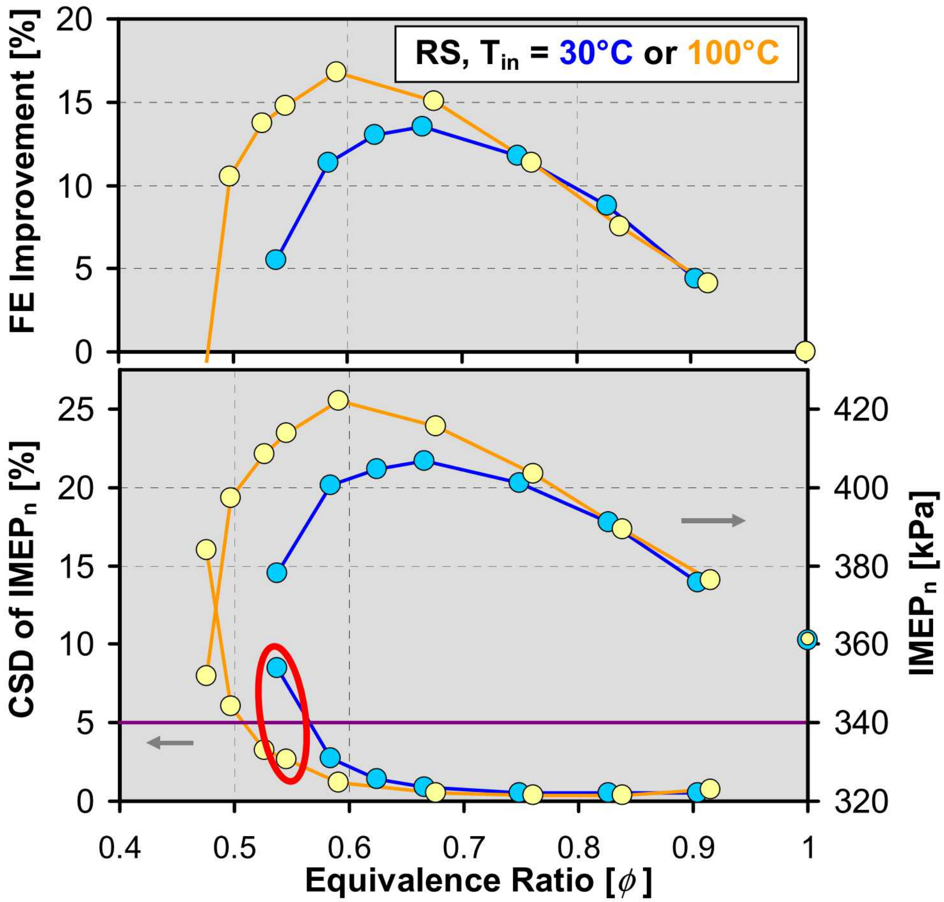




E85, T_{in} Effect

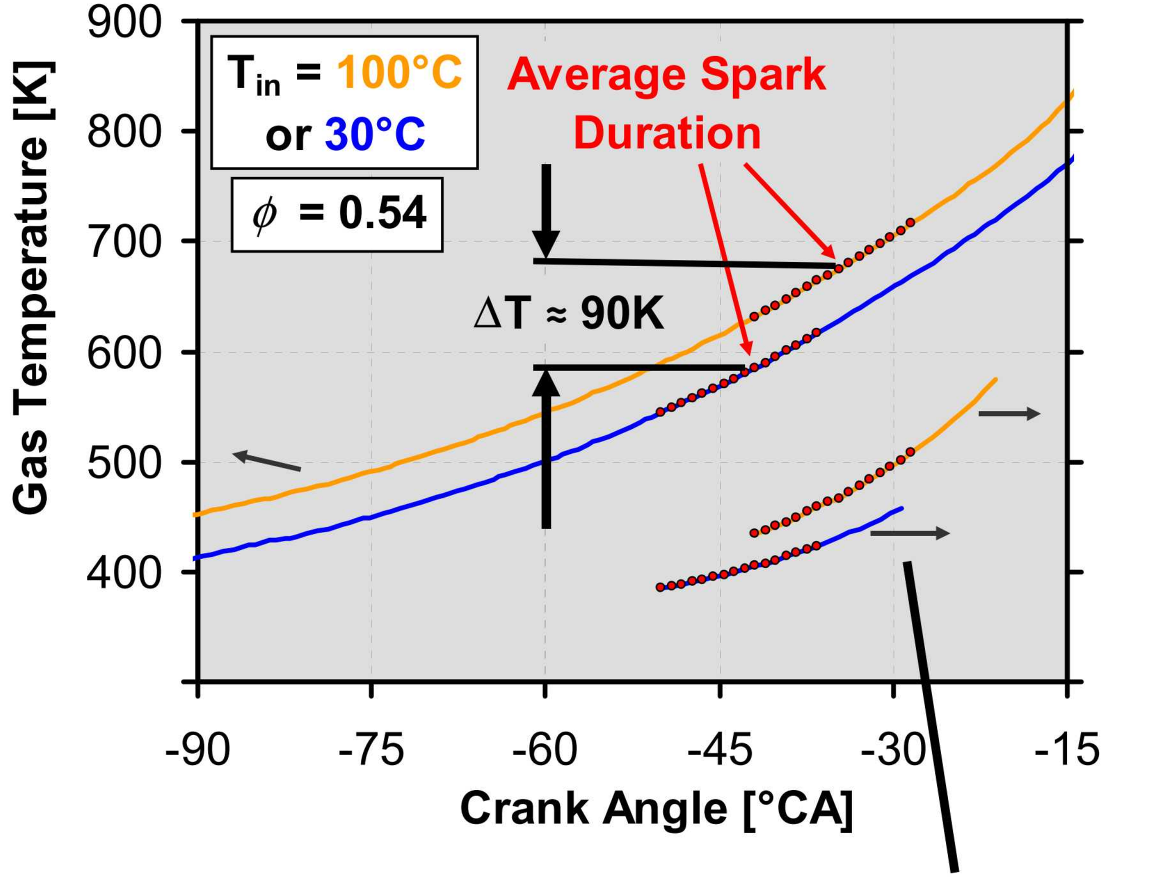
- Higher T_{in} improves lean operation.
  - Higher FE gain of 17%.
  - Leaner stability limit.
- Remarkably strong effect of 40K.





E85, Combined ST & T_{in} Effects

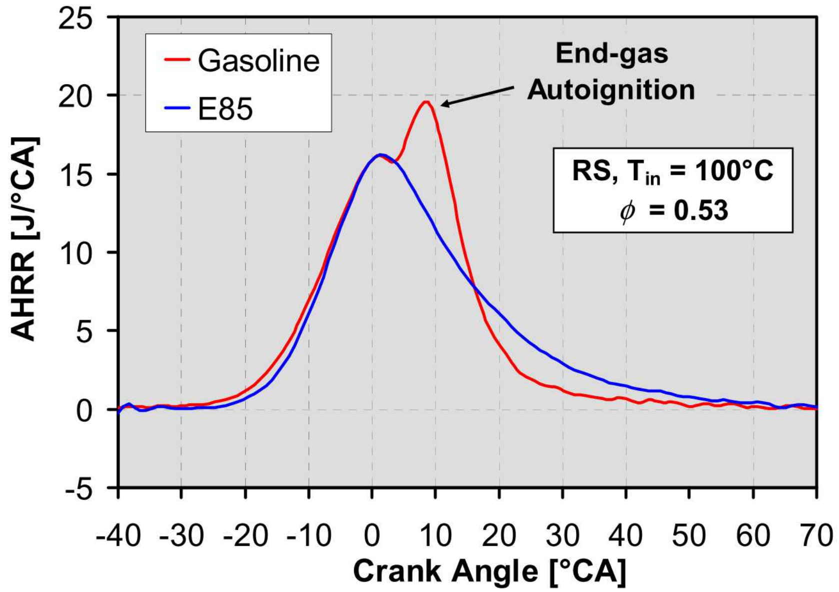
- Higher T_{in} allows later spark ⇒ Enhances effect of higher T_{in}.
- ΔT during spark event is ≈90K.
- Large relative increase of S_L.

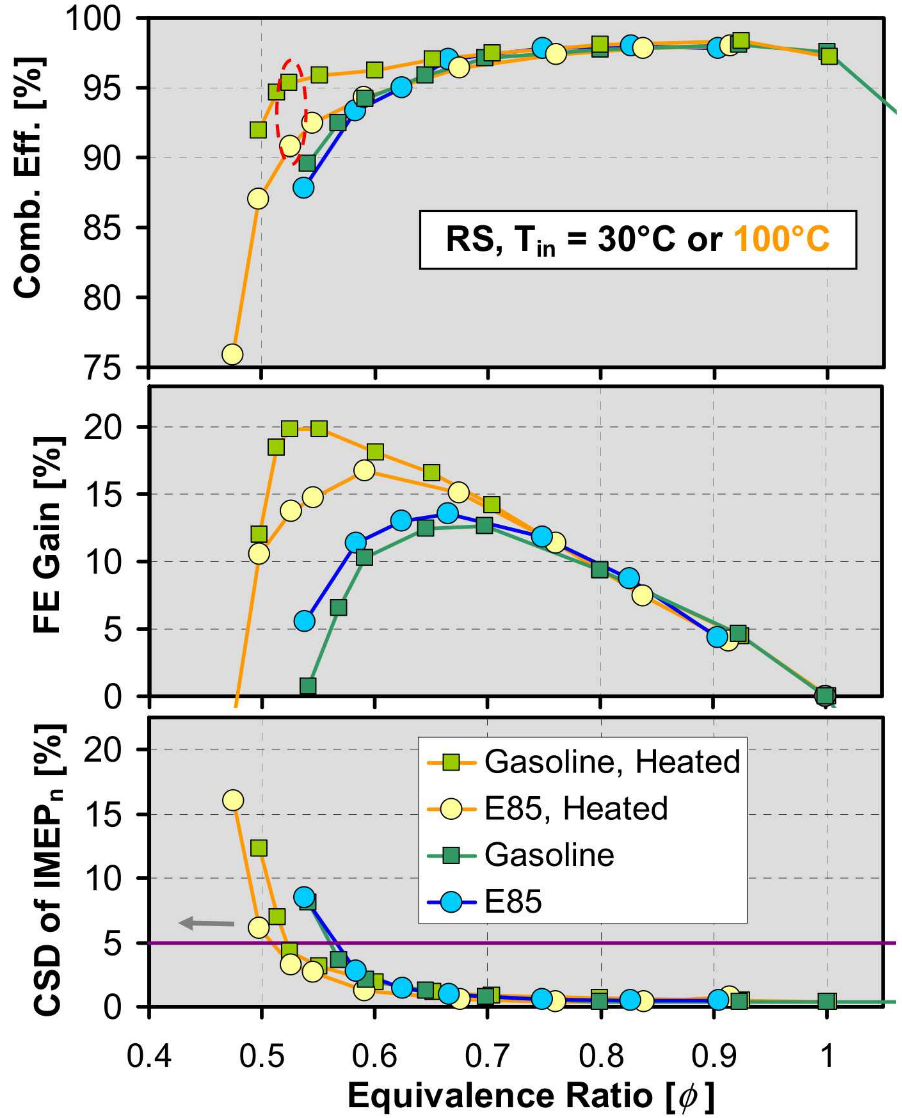


Courtesy of M. Mehl at LLNL

T_{in} Effect Gasoline

- Higher T_{in} benefits gasoline variability slightly less than E85.
- For FE gain, increased T_{in} benefits gasoline more: +20%.
- Maintain CE >95% down to ϕ = 0.53.
- Gasoline is relatively reactive.
  - Repeatable endgas autoignition.



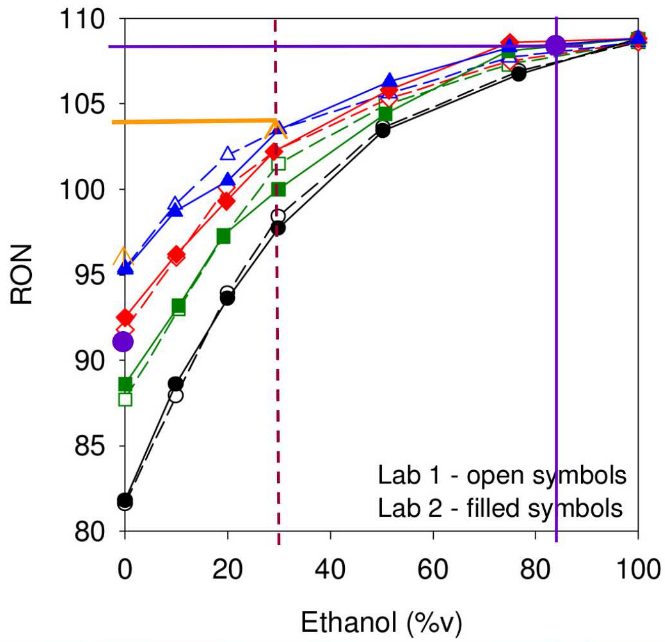


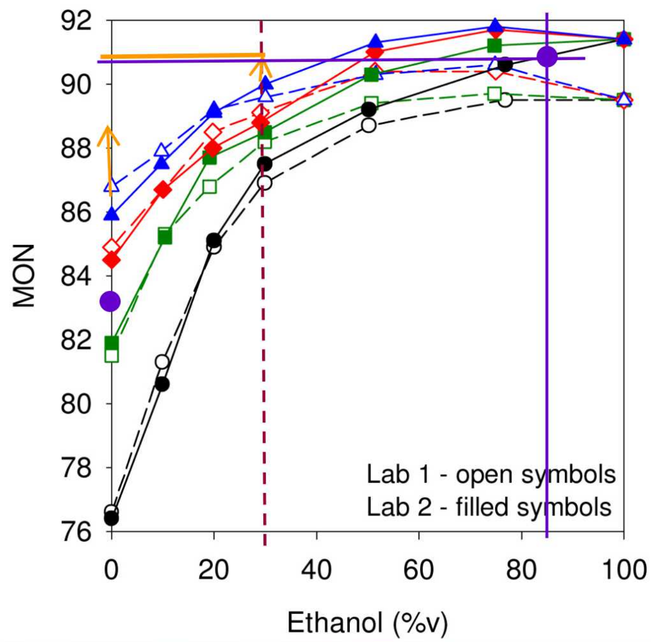
Octane Numbers

- High-octane certification **gasoline**.
  - Used for all gasoline data here.
- **E30** was blended of anhydrous ethanol and certification gasoline.
  - 30% / 70% blend ratio ⇒ E30.
- **E85** was blended from another lower-octane gasoline.
- Estimate RON & MON from SAE Paper 2012-01-1274, Anderson *et al.*

RD3-87

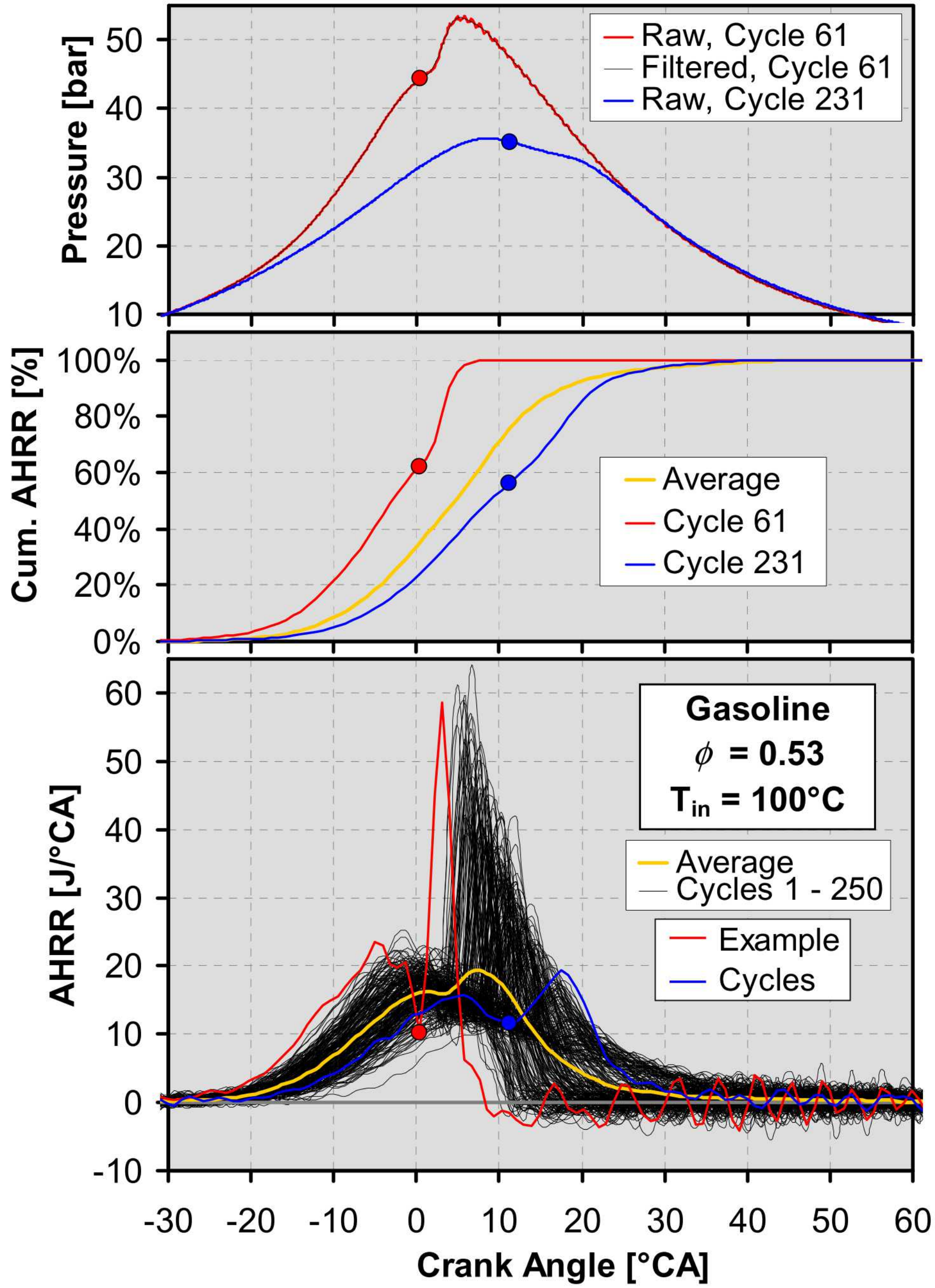
	Gasoline	⇒ E30	E85
AKI (R+M)/2	92.7	97.5	≈99.5
RON	96.6	104	≈108
MON	88.7	91	≈91
A/F Stoich.	14.6	12.8	9.8





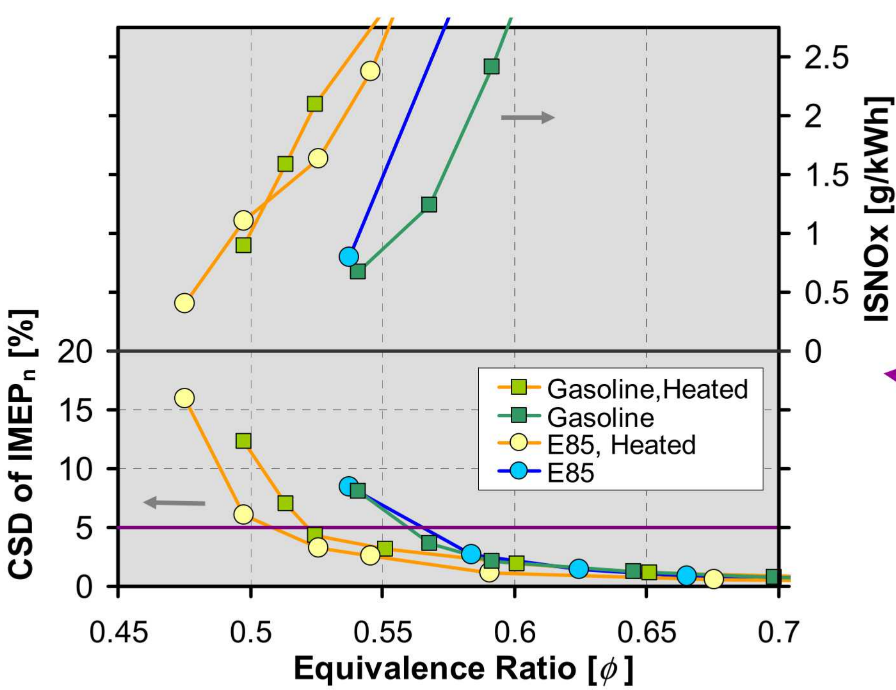
AHRR Lean Heated Gasoline

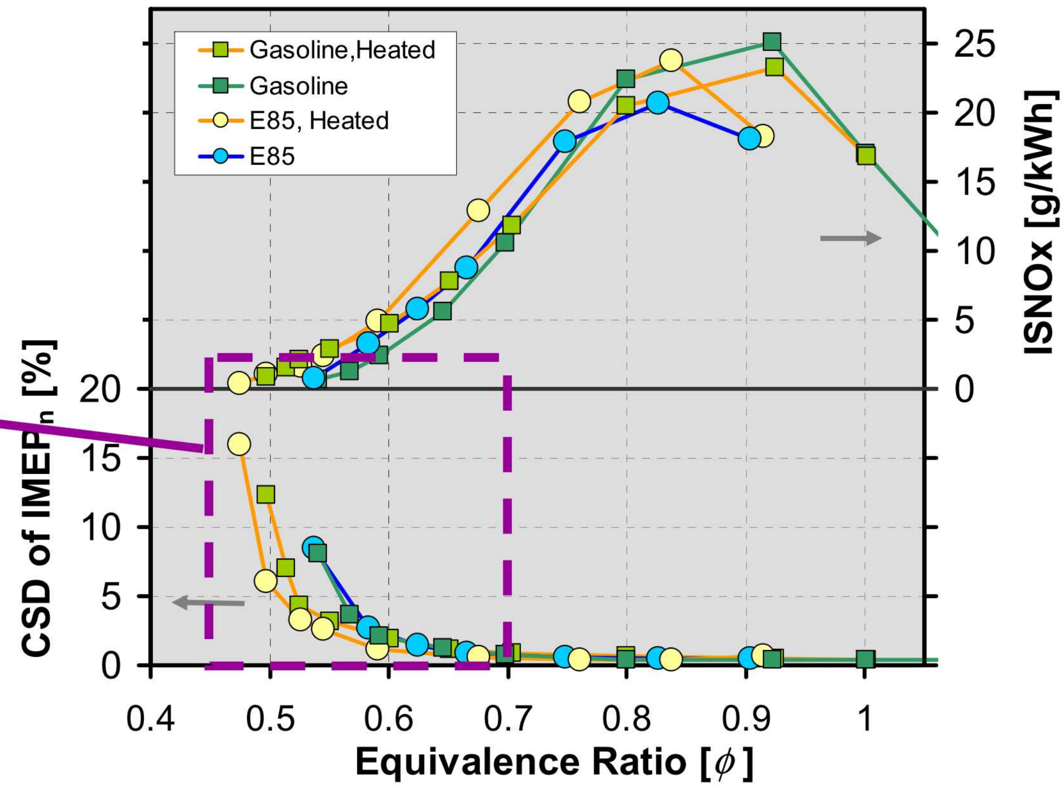
- Even with MON = 88.7, gasoline is sufficiently reactive.
- Deflagration ⇒ end-gas autoignition.
- Like SACI, but coming from SI side.
- Deflagration accounts for ≈60% of combustion event.
- Pressure ripple is mild even for the most advanced cycles.
- More repeatable deflagration should stabilize endgas autoignition.
- Here, ST = -53°CA.
  - Long inflammation period.
- Later spark with an "enhanced" ignition system should reduce variability.



NO_x Emissions

- NO_x trends and levels are comparable for gasoline and E85.
- Only beyond the lean stability limit of 5% are we reaching less than 1 g/kWh.
- 1 g/kWh = 4 g/kg gasoline.
- Lean NO_x aftertreatment may be challenging.
- Revert to dilute ϕ = 1 with TWC?



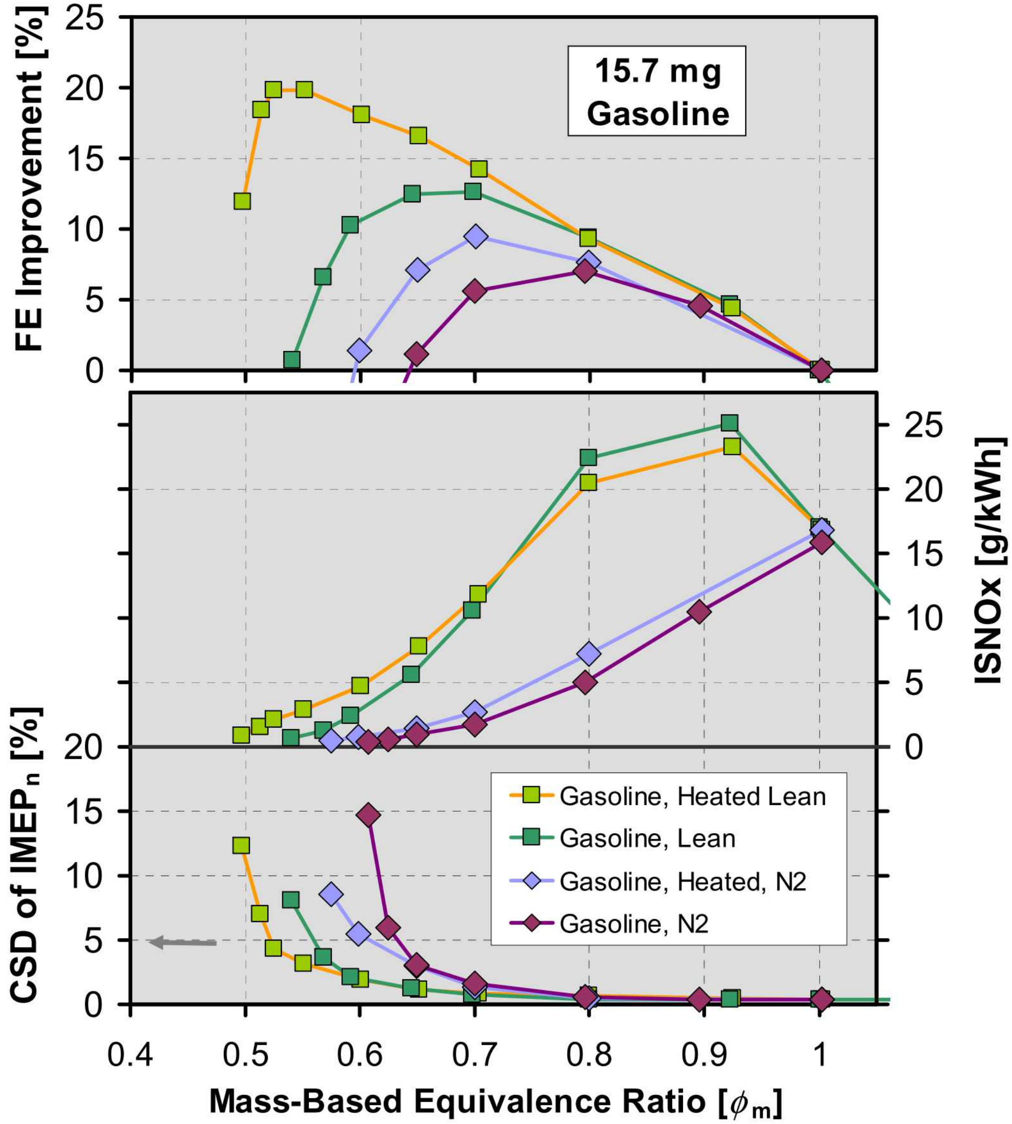


Dilute Gasoline Operation

- Dilute $\phi = 1$ operation leads to lower NO_x, **and** a three-way catalyst (TWC) can be used.
- Dilute limits are much worse than for lean operation.
- Less than 10% FE improvement for heated dilute operation.
- What is the problem?

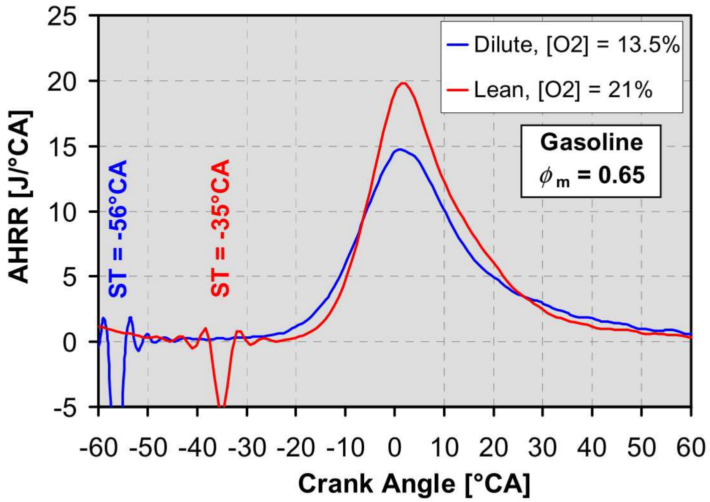
$$\phi_m \equiv \frac{\left(F/C\right)_{Actual}}{\left(F/A\right)_{Stoichiometric}}$$

- ϕ_m is a measure of chemical energy per reactant mass.
- F = **F**uel mass, A = **A**ir mass.
- C = Gas **C**harge Mass (in this case Air + N_2).

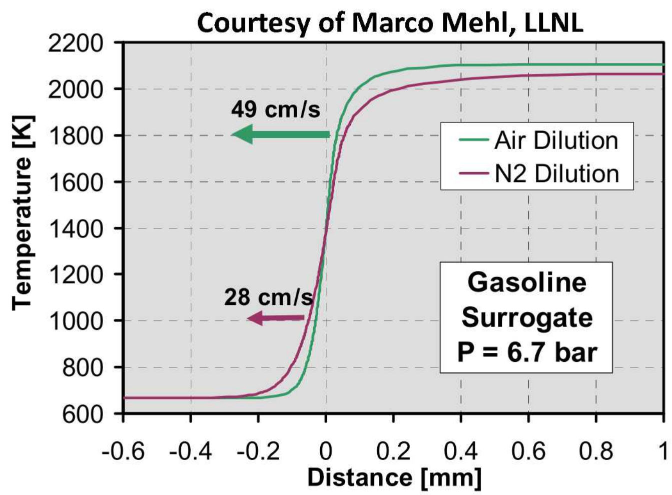


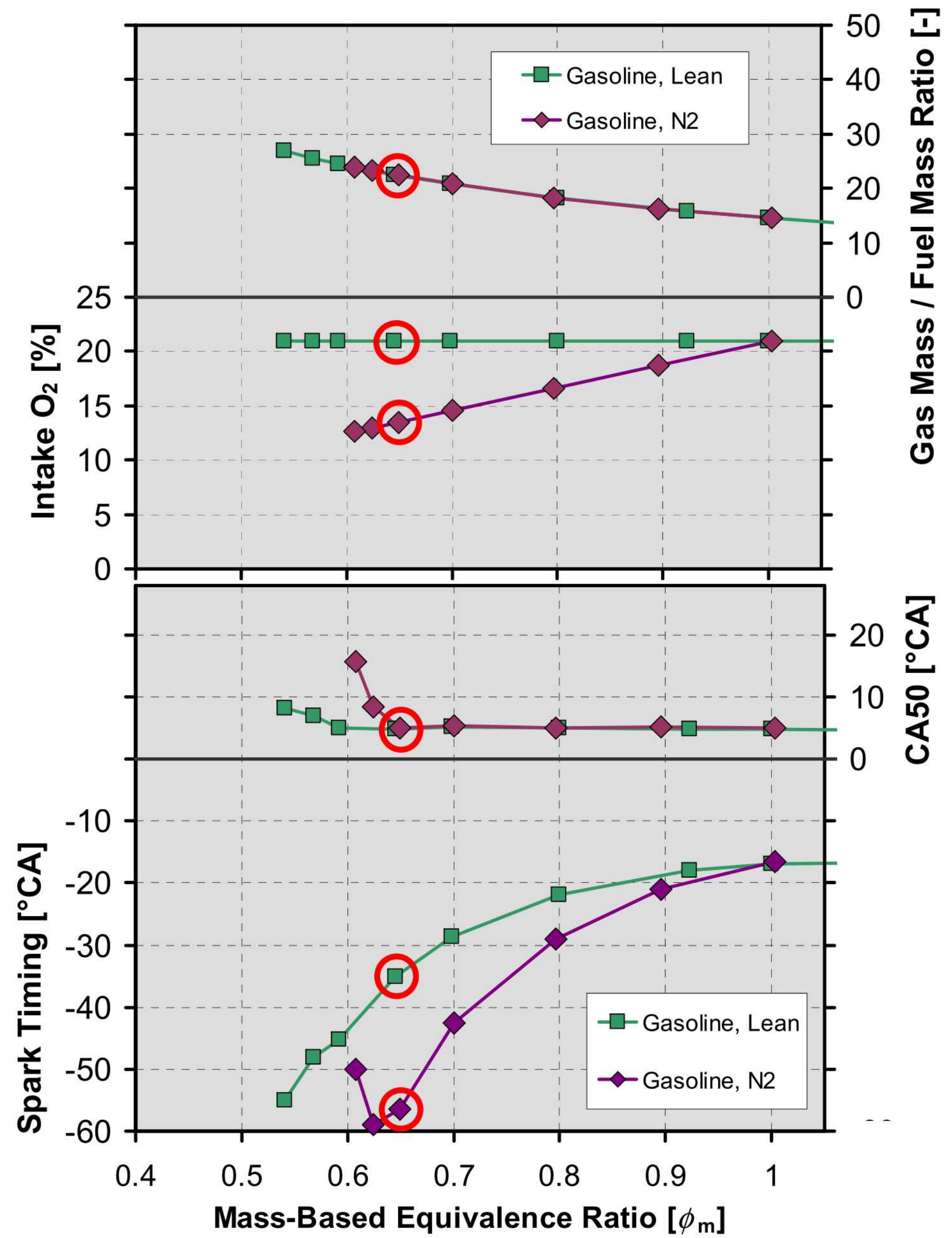
AHRR for Dilute Operation

- Dilute $\phi = 1$ operation leads to much slower spark-to-CA50.
- $[O_2]$ has huge effect on deflagration rates for early flame.

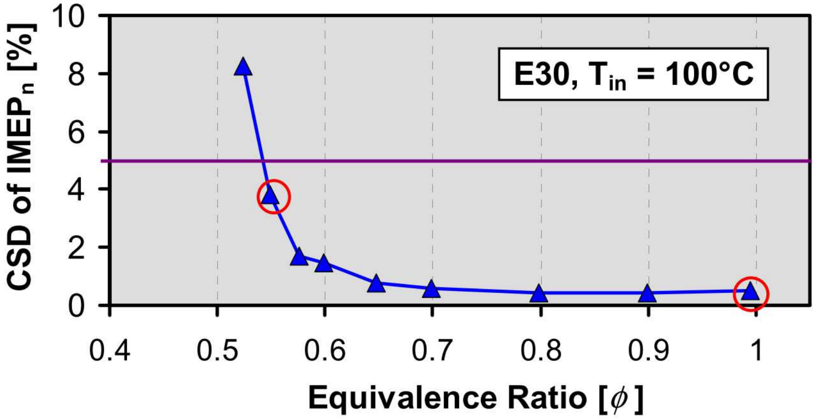


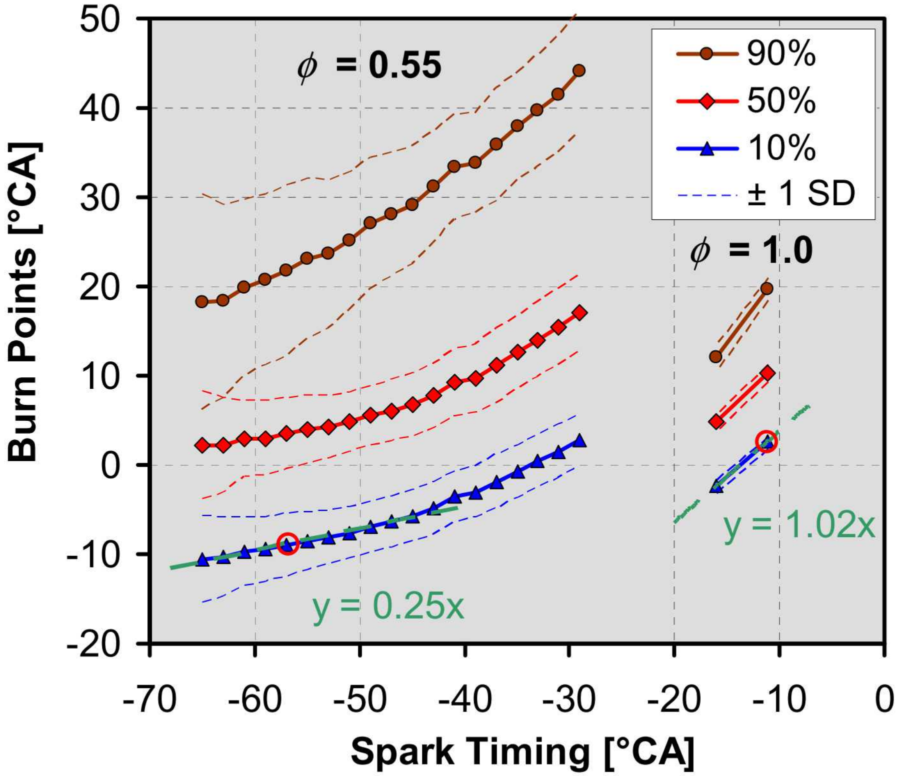
- Confirmed by CHEMKIN modeling.





Lean E30 – Combustion Control

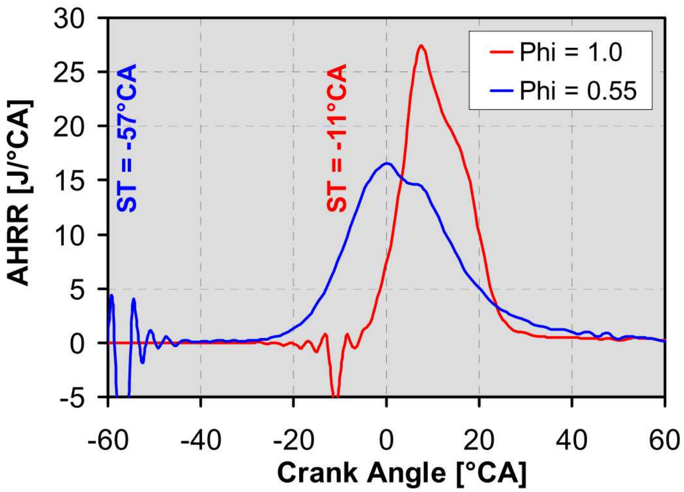




- Stoichiometric combustion:
  - Spark provides very effective combustion-phasing control.
- Near lean-stability limit:
  - Spark has lost most of its

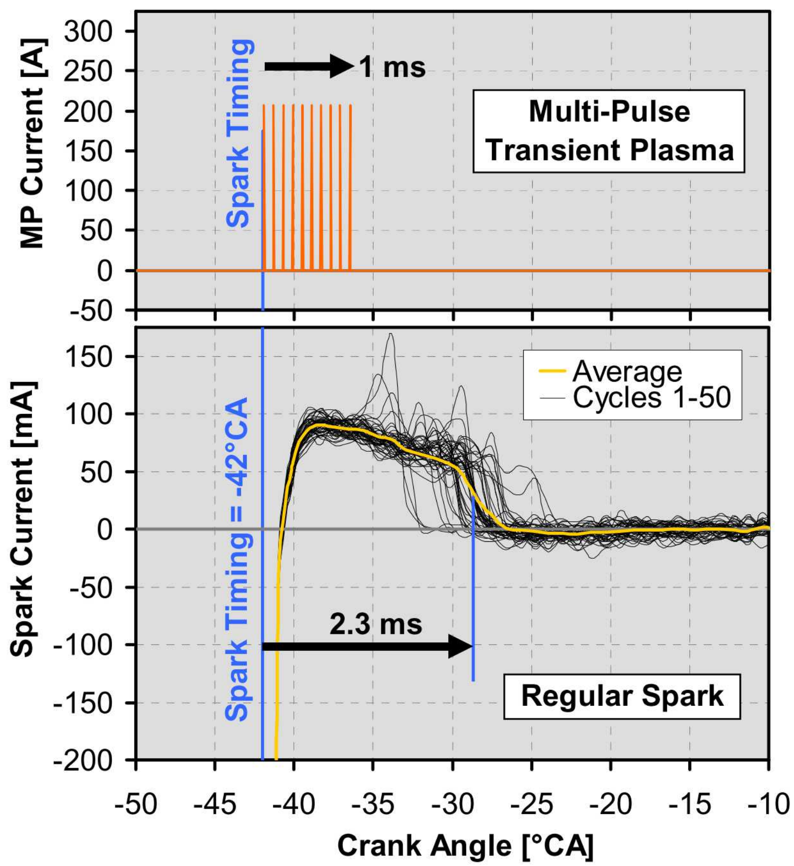
$$\textbf{control authority} = \frac{\Delta CA10}{\Delta ST}$$

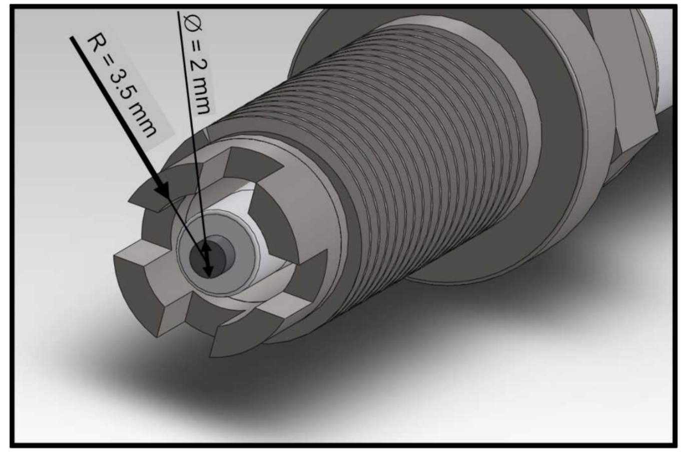
  - Slow early flame development.
  - Use advanced ignition to restore control?



Multi-pulse (MP) Transient Plasma

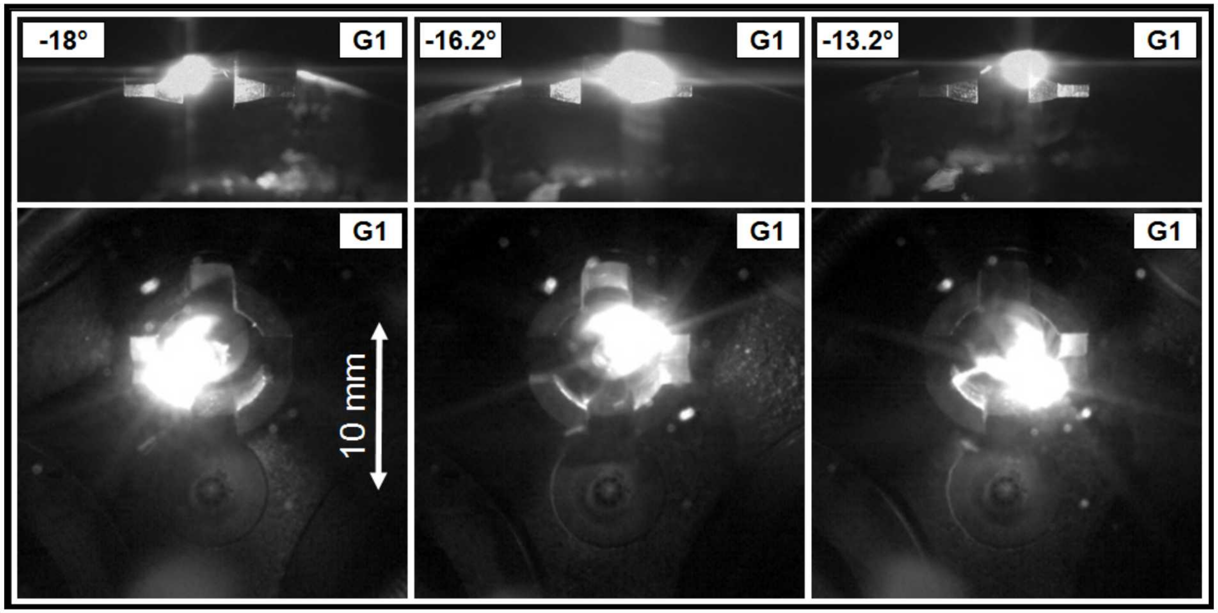
- Examine results from SAE Paper 2014-01-2615.
- Collaboration with Martin Gundersen, Dan Singleton & Jason Sanders. USC
- Modified spark plug. 4 grounding arms.
- 10 ultra-short high-current pulses over 1 ms.



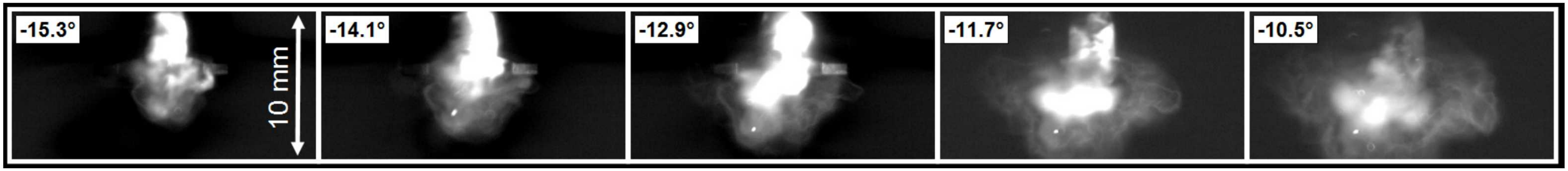


MP Example at $\phi = 0.90$, E85.

- Typically only one or two anodes show strikes.

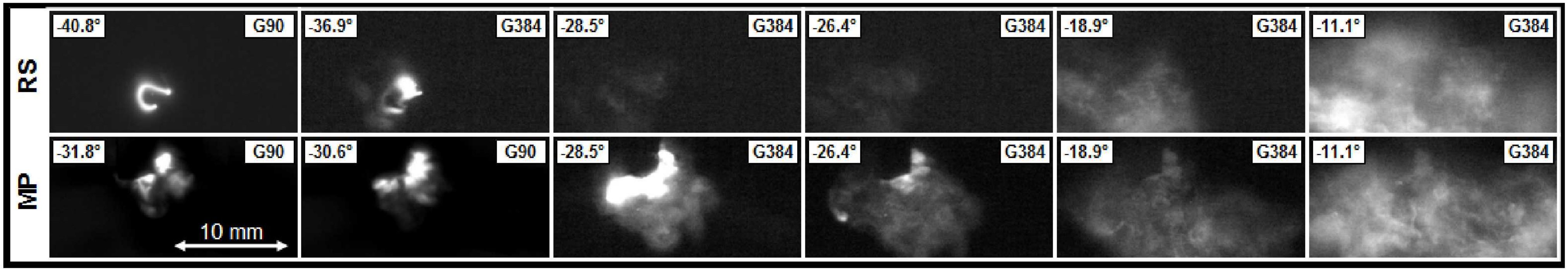


- Downward turbulent flame jet.

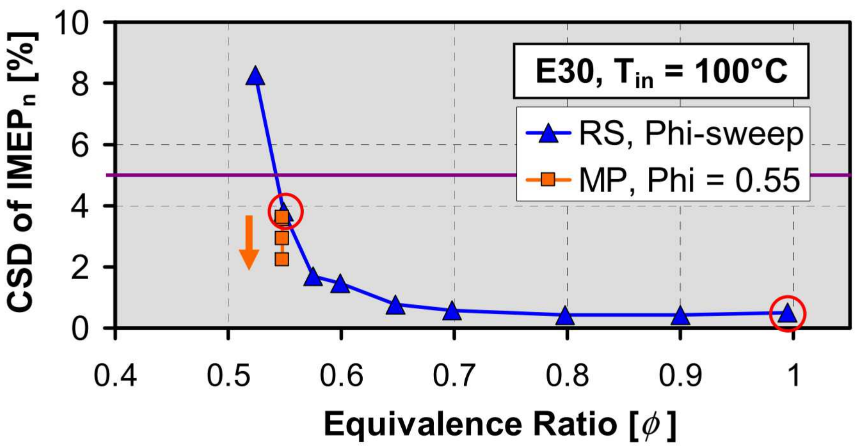


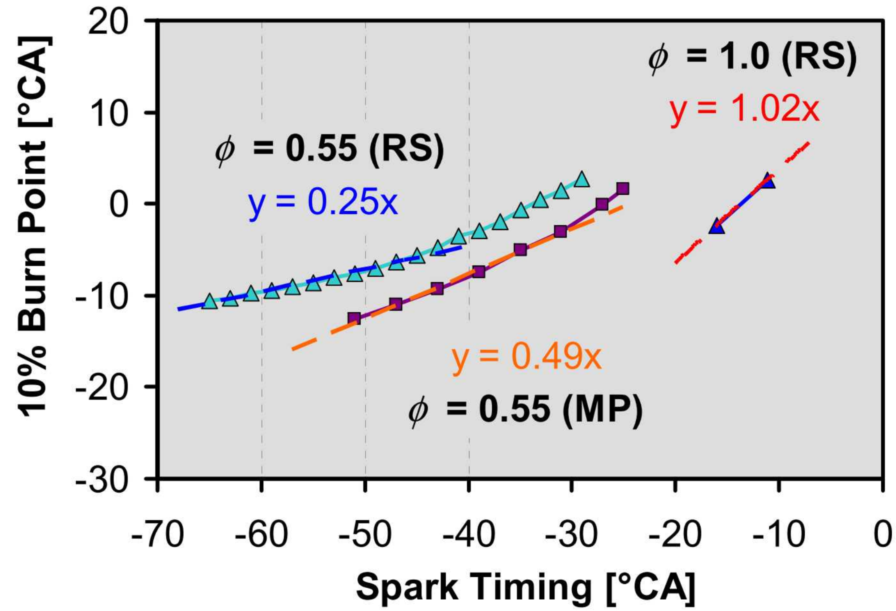
Dual-views at $\phi = 0.63$, E85

- MP "bypasses" slow and fragile early laminar flame period.

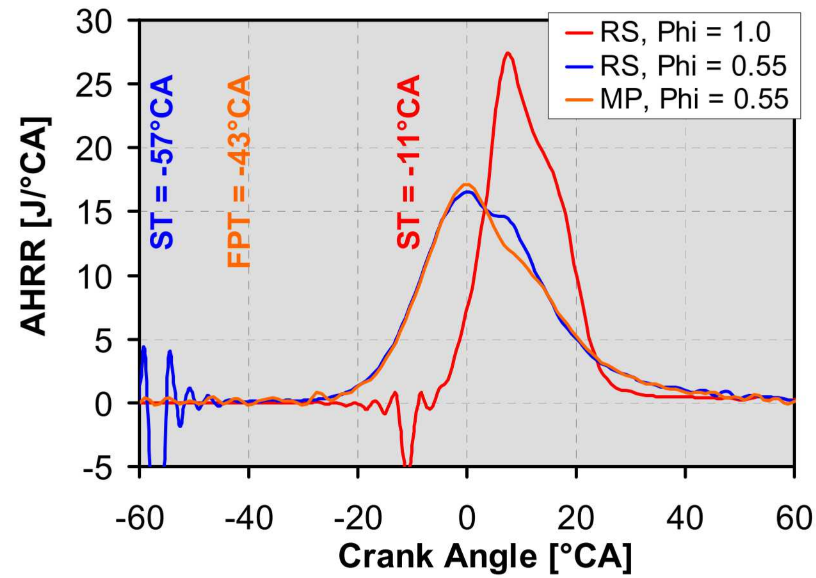


Lean E30 – Combustion Control with MP



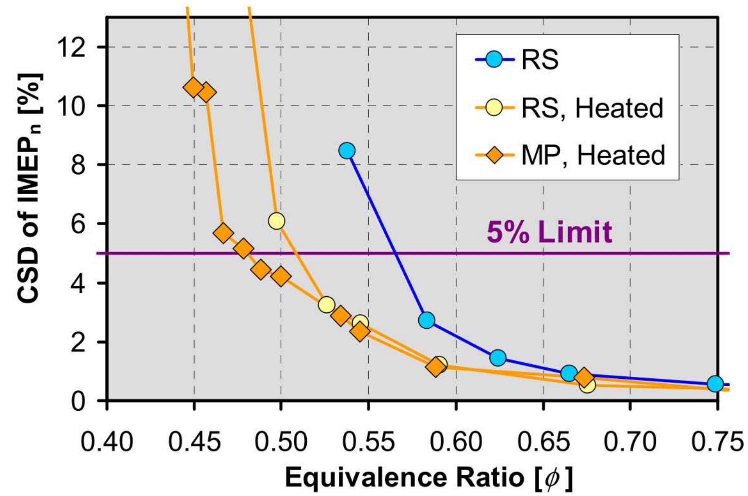


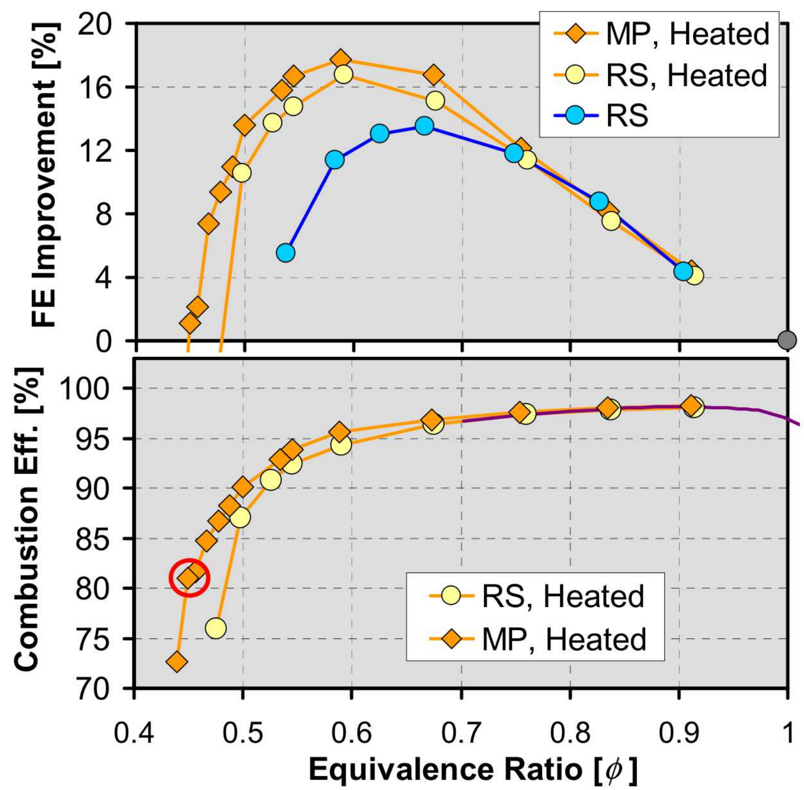
- Near lean-stability limit:
  - Spark has lost most of its authority.
  - Slow early flame development.
- 10-pulse transient plasma ignition doubles control authority.
  - Shorter ST – CA10 delay.
  - Use to lower variability.
  - Extend lean limit.

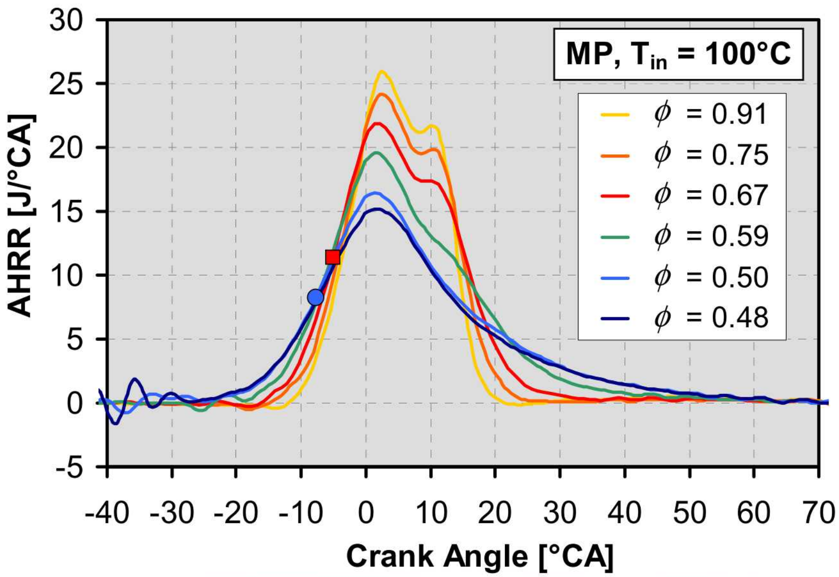


E85: FE Gain Limited by Comb. In-Eff.

- Heated MP improves lean stability limit.
- ≈18% FE improvement.
  - Only small benefit relative RS.
- Average η_{comb} suffers at stability limit.
- Slow and erratic burn out.
- Enabling step: Ensure complete and faster combustion for all cycles.
- Provoke end-gas autoignition.
- Challenging for high-octane E85.

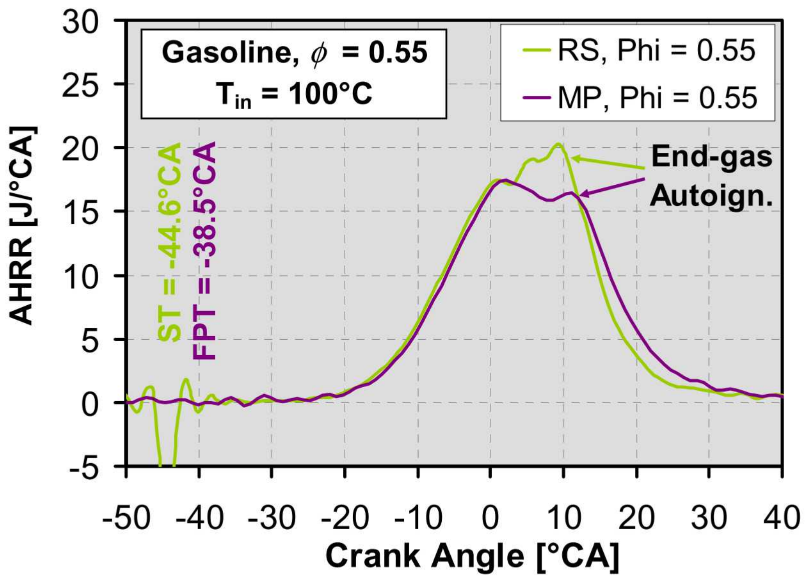


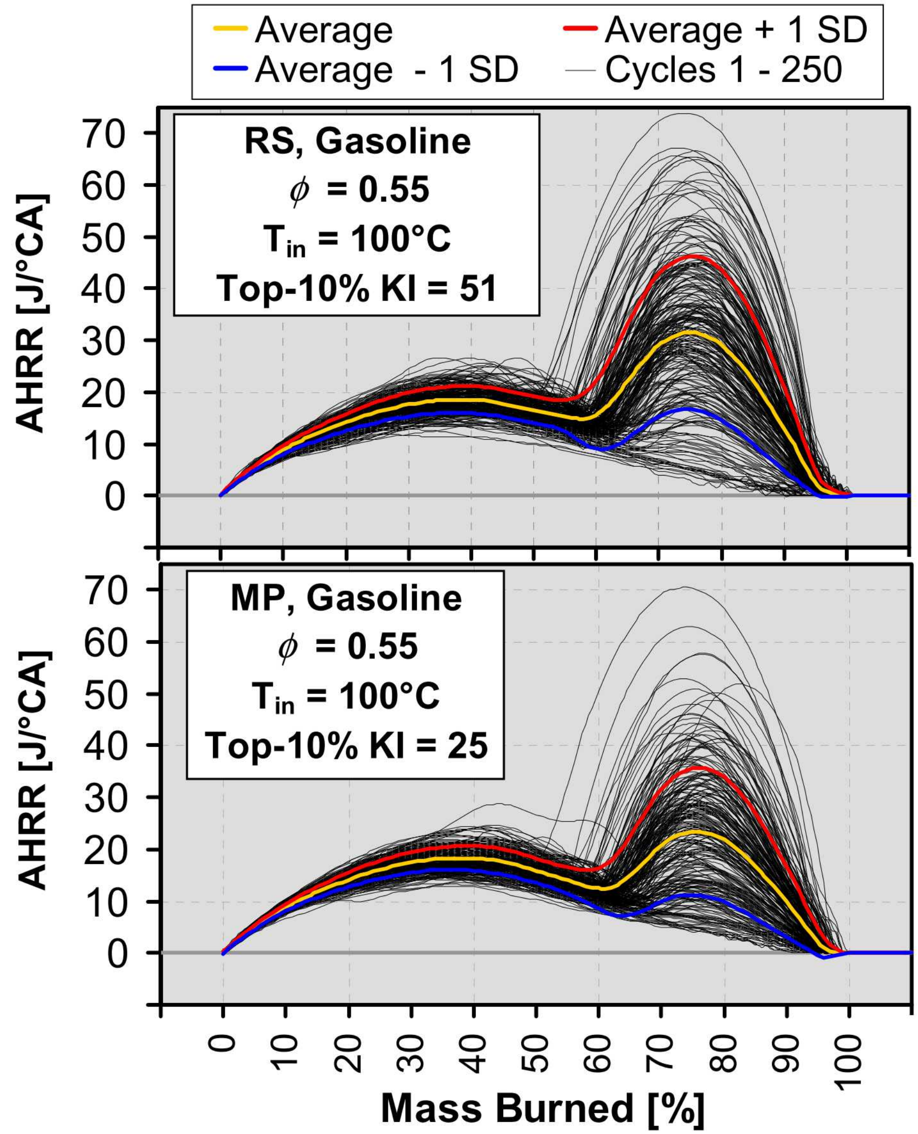




Improve End-gas Autoignition Control

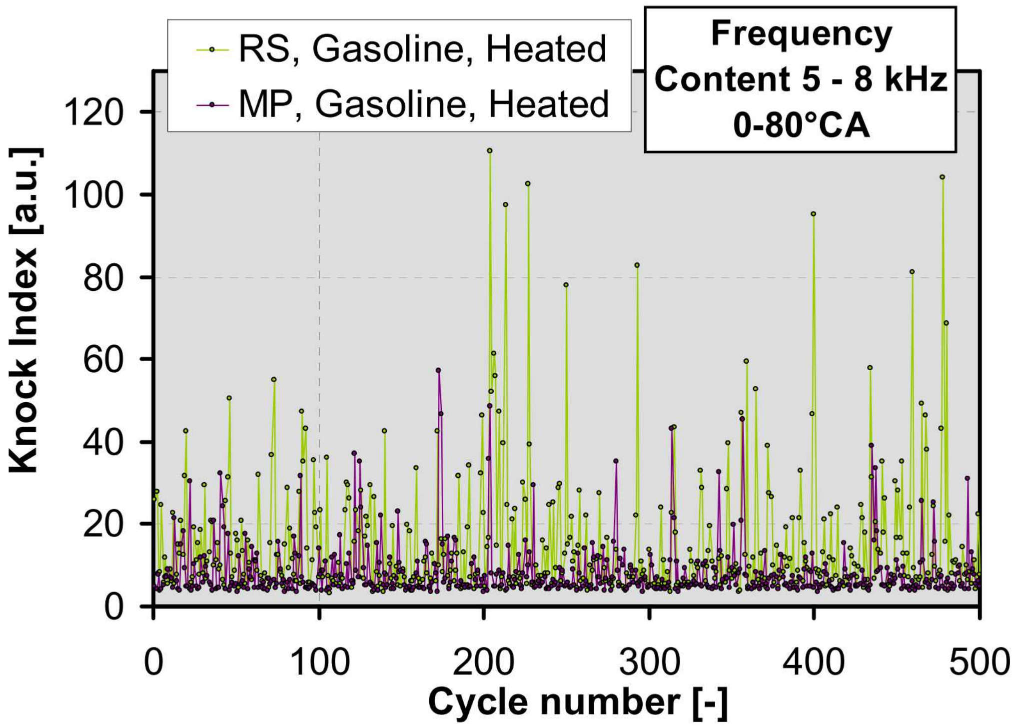
- Better control with MP allows later CA50 for ultra-lean SI gasoline operation.
- Average burn-point for end-gas autoignition shifts 58 to 62% ⇒
  - CAI portion reduced from 42 to 38%.
  - More repeatable combustion.
  - Fewer outlier cycles.

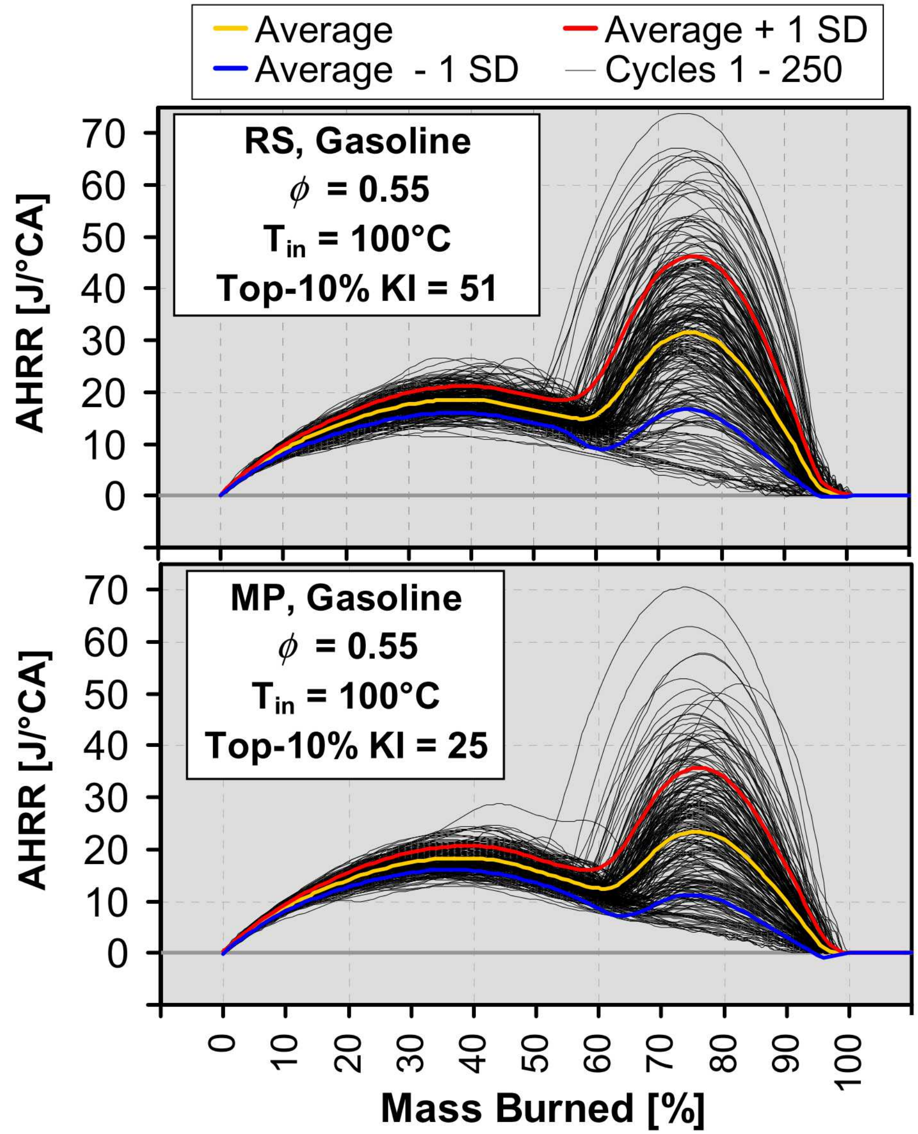




Reduction of Knocking Cycles

- Fewer outlier cycles ⇒ Knock index (KI) for top-10% cycles cut in half.



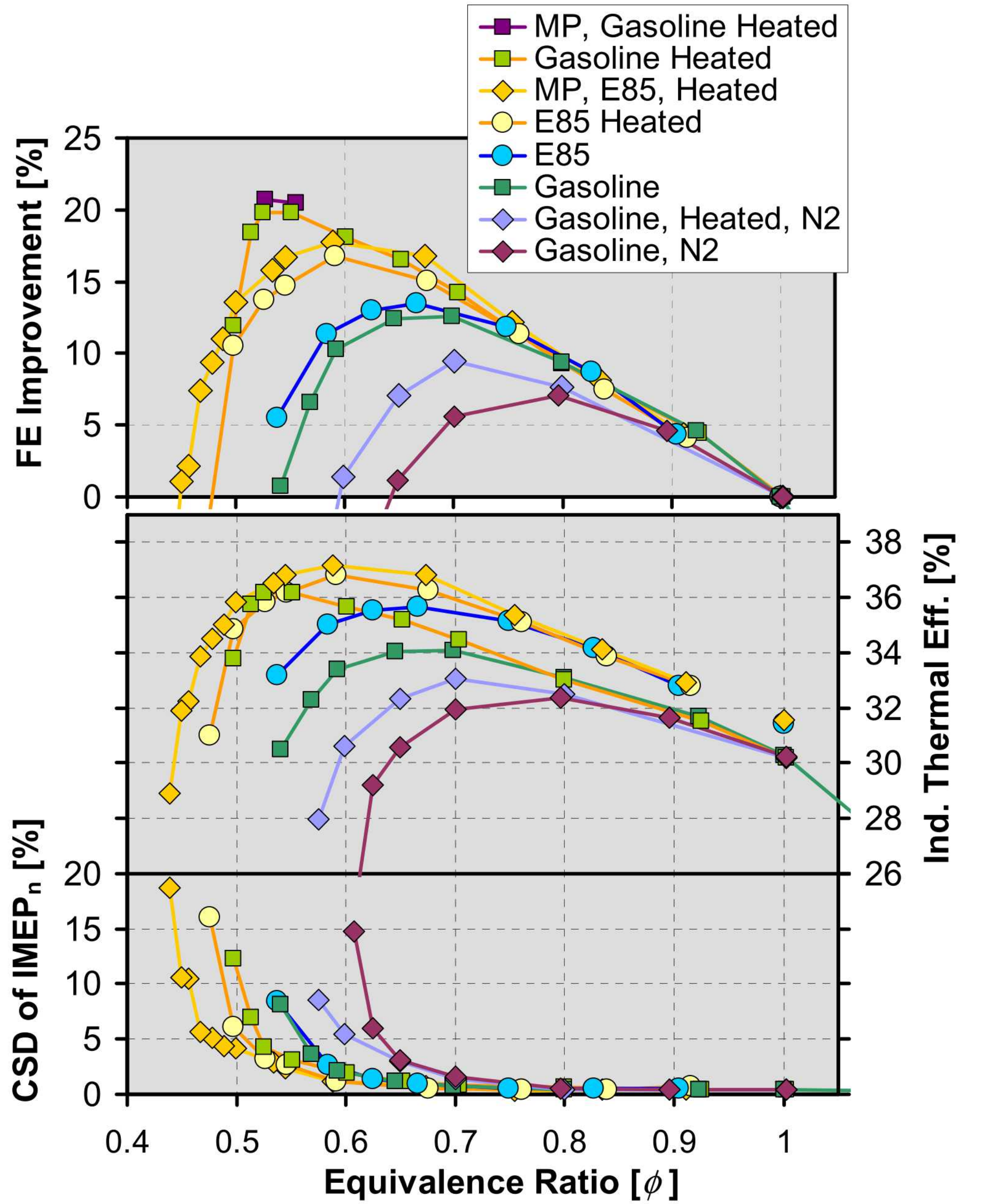


Summary of Results at 1000 rpm

- MP Heated Gasoline leads to slightly larger FE improvement.
- Data sets sorted by 5% variability limit:

Operation	Max FE Impr.	Peak TE	Limit [ϕ_m]
Heated E85, MP	17.7%	37.2%	0.480
Heated E85	16.8%	36.8%	0.508
Heated Gasoline	19.9%	36.2%	0.522
Gasoline	12.6%	34.1%	0.560
E85	13.5%	35.7%	0.565
Heated Gasoline, N_2	9.4%	33.0%	0.608
Gasoline, N_2	7.0%	32.4%	0.632

- E85 data sets have higher TE for $\phi = 1$.
- Peak TE are also higher.
  - Benefit of vaporization cooling.
  - ⇓ comb. temps. & γ ⇑.



Conclusions

- Fuel-savings potential of dilute stoichiometric SI operation appears limited by very slow early flame development.
  - Need for highly enhanced ignition source to examine ultimate potential.
- Lean SI operation has substantial potential for efficiency gains, even with regular spark ignition.
- Fuel-economy gains are limited by combustion variability and inefficiencies.
- Stable combustion is promoted by:
  - Late spark timing for a given CA50.
  - High charge temperature at the time of spark.
  - Not relying on fragile early laminar flame.
- Multi-pulse transient plasma ignition with a semi-open spark geometry provides more stable lean combustion by creating a turbulent flame jet.
  - Bypassing phase with slow and fragile laminar flame.
- High combustion efficiency for ultra-lean operation requires end-gas autoignition.
  - Fuel reactivity becomes important.
- With better ignition-control authority for ultra-lean operation, end-gas autoignition becomes more repeatable.