Low-Temperature Gasoline Combustion (LTGC) Engine Research

– Previously known as HCCI / SCCI –

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June 17, 2014 – 12:00 p.m.

U.S. DOE, Office of Vehicle Technologies
Annual Merit Review and Peer Evaluation

Program Managers: Gurpreet Singh & Leo Breton **Project ID: ACE004**

Overview

Timeline

- Project provides fundamental research to support DOE/Industry advanced engine projects.
- Project directions and continuation are evaluated annually.

Barriers

- Increase the efficiency of LTGC / HCCI.
- Extend LTGC / HCCI operating range to higher loads.
- Improve the understanding of in-cylinder processes.

Budget

- Project funded by DOE/VT:
  FY12 – $740k
  FY13 – $720k

Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – in-depth collaboration
- Cummins – spark-plug cylinder heads
- LLNL – support kinetic modeling
- Univ. of Calif. Berkeley – CFD modeling
- Univ. of Melbourne – biofuels & kinetic modeling
- Chevron – advanced fuels for LTGC

Objectives - Relevance

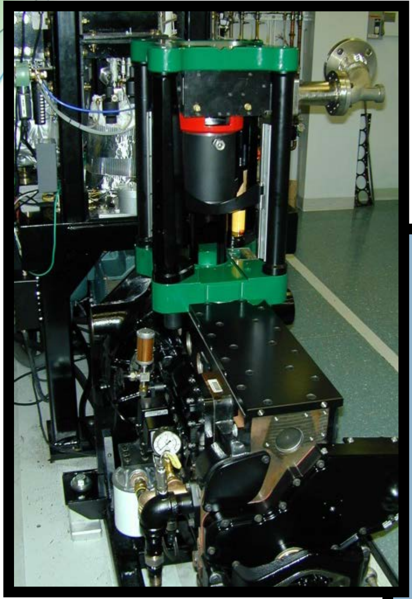
<u>Project objective</u>: to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical LTGC / HCCI engines by industry.

<u>FY14 Objectives</u> ⇒ Increased Efficiency, High Loads, Improved Understanding

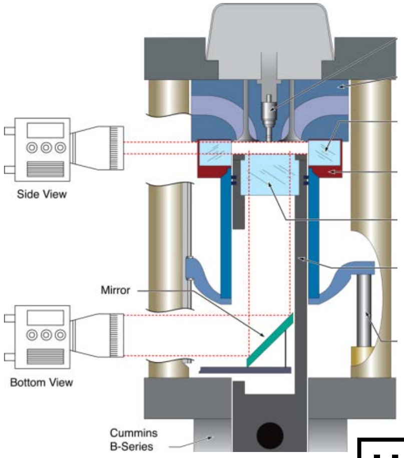
- <u>High-load Limits for CR =16</u>: Determine high-load limits for a range of boost pressures (P_{in}) and speeds. ⇒ Also, potential of Miller cycle to incr. load.
- <u>Noise analysis:</u> Comprehensive study of CNL and RI over range of conds.
- <u>High-Efficiency LTGC</u>: Examine factors affecting measurement of Thermal Efficiency (TE). ⇒ Clarify differences between LTGC and RCCI & CDC.
- <u>Evaluate potential of improving TE over load range</u> with Partial Fuel Stratification (PFS) by optimizing GDI fuel-injection strategy (<u>multi-year task</u>)
- <u>Fuel-Distribution Imaging</u>: Apply PLIF imaging in optical eng. to understand how GDI strategies affect ϕ-distribution, to help optimization (<u>multi-year task</u>)
- <u>Complete Facility Upgrade</u> for spark-assist, higher GDI $P_{injection}$, & lower swirl
- <u>Support Modeling</u>: Chemical-kinetics at LLNL & CFD at UC-Berkeley & GM.

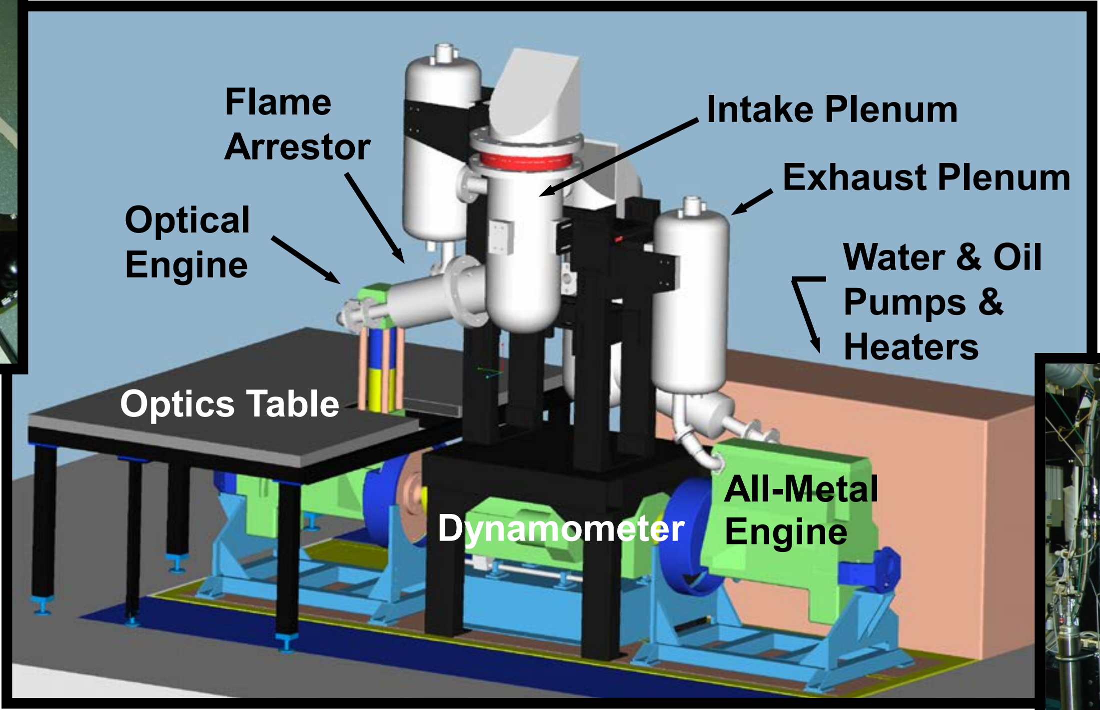
Sandia LTGC Engine Laboratory

- Matching all-metal & optical LTGC research engines.
  - Single-cylinder conversion from Cummins B-series diesel.

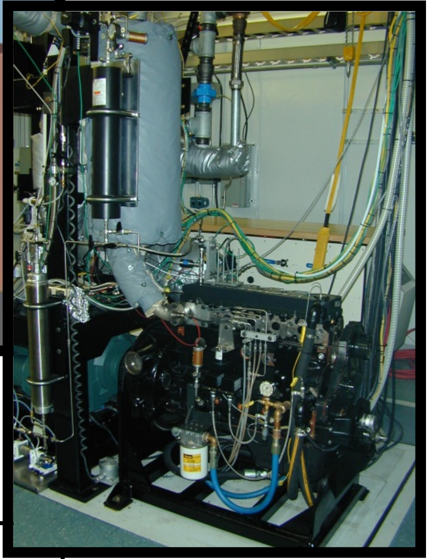


Optical Engine





All-Metal Engine



- Bore x Stroke = 102 x 120 mm
- 0.98 liters, CR=14 & 16

Unless noted: Ringing ≤ 5 MW/m^2 & spd = 1200 rpm
NO$_x$ & soot emiss. > 10x below US-2010

Approach

- Use a combination of metal- and optical-engine experiments and modeling to build a comprehensive understanding of LTGC / HCCI processes.

- **Metal Engine** ⇒ high-quality performance data ⇒ well-controlled experiments
  - High-Load Limits: Adjust CA50 as fueling increased for good stability and no knock.
  - Noise Study: Analyze combustion noise level (CNL) & ringing intensity (RI) for wide range conditions. Investigate fundamental causes of differences between CNL & RI.
  - High-Efficiency Studies: 1) Analyze all factors affecting measurement of TE; 2) Sweep parameters to find highest TE; 3) Effects of GDI timing & multiple injections.
- **Optical Engine** ⇒ detailed investigations of in-cylinder processes.
  - Fuel Distribution Imaging: 1) PLIF imaging calibrated in-situ; 2) Vertical laser sheet to see all elevations, 3) Obtain ϕ-map images for various fuel-injection strategies. ⇒ **Guide application of PFS in metal-engine for higher TE** ⇒ **Model validation**
- **Computational Modeling**: **1)** Collaborate with UC-B and GM on CFD modeling for improved understanding of PFS ⇒ **Results guide experiments for higher TE.** **2)** Work with LLNL to improve kinetic mechanisms of gasoline/ethanol blends.
  - **Contribution:** identify key trends, provide validation data, discussion & feedback.
- Combining techniques provides a better understanding & more-optimal solutions
- **Transfer results to industry:** 1) physical understanding, 2) improved models.

Approach - Milestones

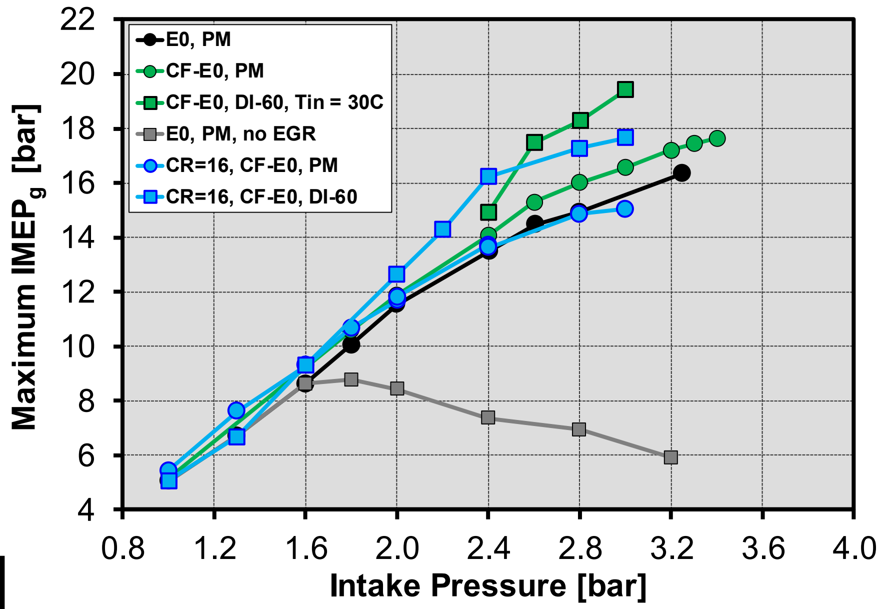
- ✓ **March 2013**
  Deduce thermal boundary-layer profiles adjacent to the cylinder-wall from temperature-map images.
- ✓ **September 2013**
  Determine the effectiveness of PFS for increasing efficiency above the values obtained with well-premixed fueling for operation with CR = 16:1.
- ✓ **December 2013**
  Determine effects of intake temperature, gasoline direct injection (GDI) timing and GDI injection pressure on maximum load and peak efficiency at a representative boosted operating condition.
- ✓ **March 2014**
  Establish optical setup and data reduction techniques for fuel-distribution imaging of DI-PFS.
- **June 2014**
  Complete investigation and first-order optimization of single-injection DI-PFS over a wide range of intake boost pressures, including maximum load and peak efficiency at each pressure.
- **September 2014**
  Complete installation and shakedown testing of new low-swirl cylinder head with spark-assist capability.

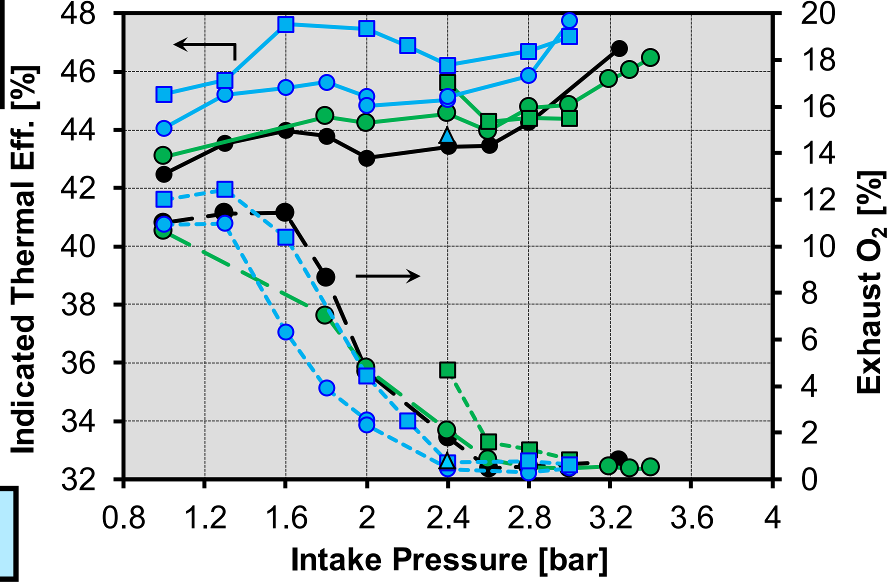
Accomplishments – Overview

- Determined **high-load limits for CR = 16** over range of P_{in} and speeds.
  - Also, conducted analysis of Miller cycle for its potential to increase load.
- Conducted extensive **study of CNL and RI** over a range of loads, P_{in}, CA50, speed & knock intensity. Also, examined & explained reasons for differences.
- In-depth investigation of all potential factors affecting **measurement of TE**.
  - Also, conducted additional parameter sweeps to determine effects on TE.
  - Compared TE of LTGC with RCCI & conventional diesel combustion (CDC).
- **Better optimized PFS** fuel distributions for improved TE over the load range.
  - Evaluated effect of GDI timing for a single-injection PFS.
  - Initial investigation of potential for further improvements with multiple injections.
- Established optical setup and characterized new back-illuminated CCD camera for quantitative fuel-distribution imaging.
  - **On track** to obtain ϕ-map images for initial GDI sweeps this FY **as planned.**
- **Facility upgrade ⇒ on track** to complete required modifications to new cylinder head for installation with 300-bar GDI and spark assist this FY.
- Collaborated with UC-B and GM on CFD modeling and LLNL on kinetics.

High-Load Limits for CR 16 ⇒ P_{in} sweep

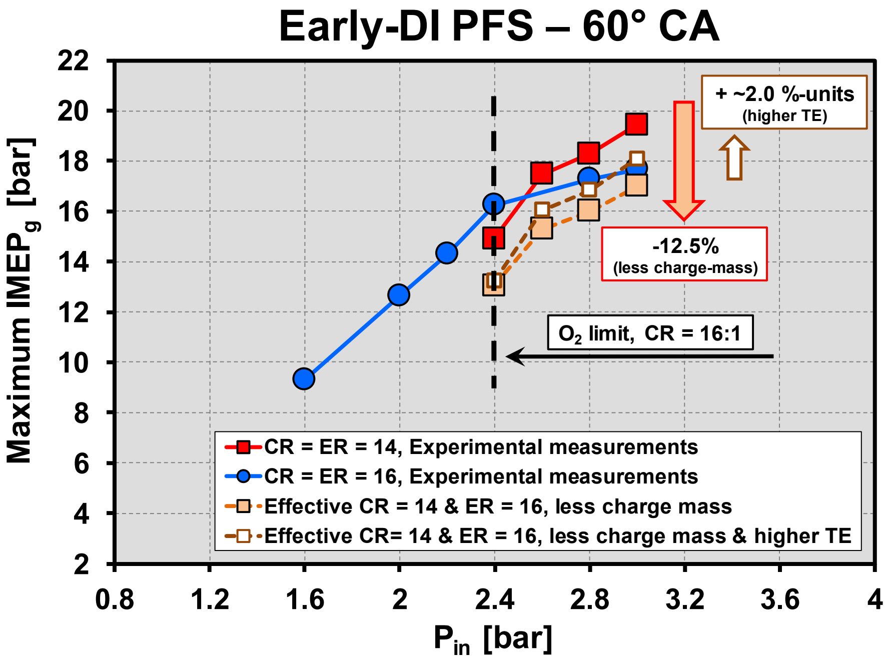
- CR = 14 results from last year:
  - Early-DI PFS gives higher loads with less boost (19.4 bar $IMEP_g$ at P_{in} = 3.0)
- Focus on CR = 16 vs. 14,
  ⇒ Using Certification Fuel (CF)
- <u>Premixed fueling</u>: CR 16 gives up to 13% higher load at low boost vs. CR 14.
  ⇒ Lower req'd. T_{in} with higher CR.
- <u>Early-DI-PFS fueling</u>: CR 16 gives higher $IMEP_g$ for 1.6 < P_{in} < 2.5 bar.
  ⇒ Greater stability allows high ϕ_m
- TEs at max. load for each P_{in} are notably higher for CR = 16, both PM, ad DI.
- Max. load at high boost is about 9% less with CR 16. ⇒ More EGR req'd. to control CA50 ⇒ limits air, so lower ϕ_m.
- Still reach 17.7 bar $IMEP_g$ at P_{in} = 3.0 bar

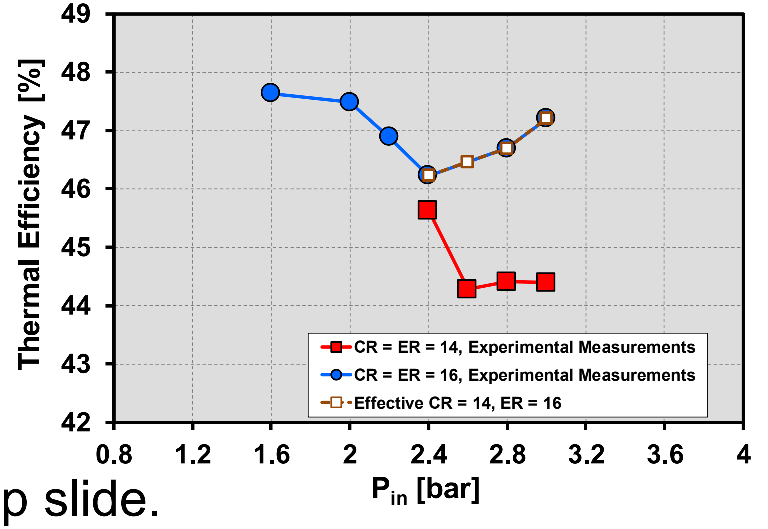




Effect of Miller Cycle ⇒ CR = 14, ER = 16

- Max. load at high boost (P_{in} > ~2.5 bar) less with CR 16. ⇒ More EGR req'd. to control CA50 advance ⇒ limits air & ϕ_m.
- Would a Miller cycle be better?
  - Reduce req'd EGR & allow higher ϕ_m.
  - But it would reduce the charge mass.
- Compute max. $IMEP_g$ for charge-mass reduction of 12.5% vs. std. valve timing.
- Increase load to account for higher TE.
  - TE gain ~2.0 %-units, quite significant.
- Standard cycle gives higher loads except for P_{in} = 3.0 bar.
  - Here, Miller cycle increases max. $IMEP_g$ from **17.7 to 18.1 bar, a marginal gain.**
- **Standard cycle seems better overall.**



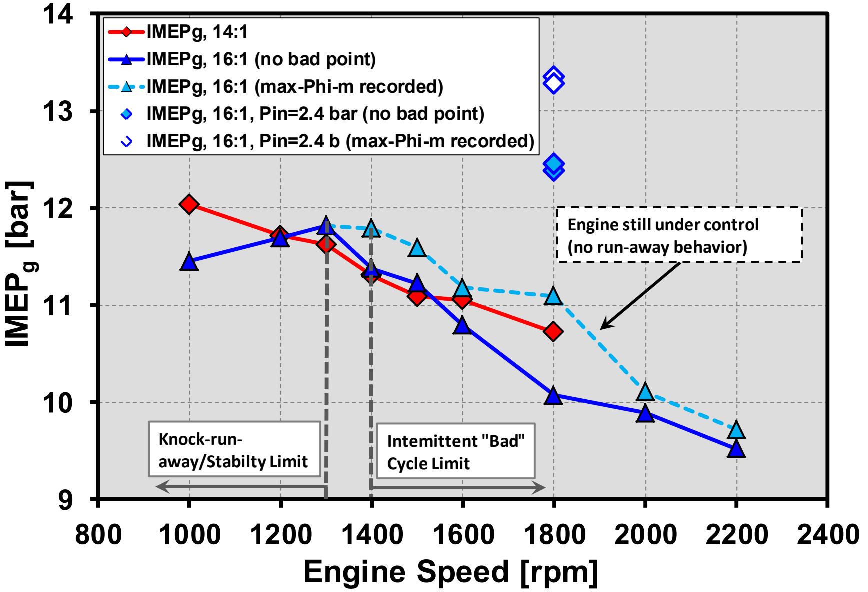


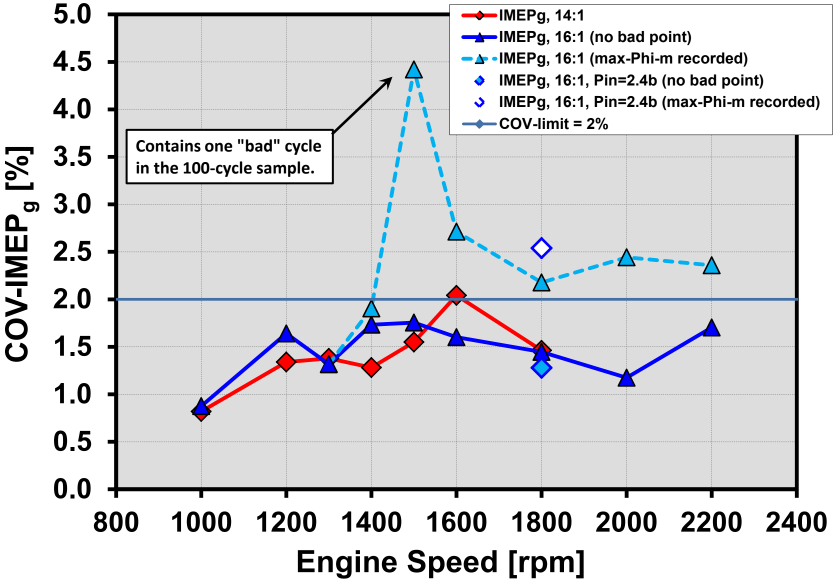
- Similar results for premixed fueling ⇒ backup slide.

High-Load Limits for CR 16 ⇒ Speed Sweep

- Determine high-load limit for CR = 16, and compare with previous data for CR = 14. ⇒ Premixed, P_{in} = 2 bar
- <u>CR = 14</u>: Consistent trend ⇒ Knock/stability limited at all speeds.
- <u>CR = 16</u>: Trend reverses at 1300 rpm
  - Typical decrease w/ speed, ≥ 1300 rpm.
  - $IMEP_g$ increases with speed ≤ 1300 rpm ⇒ Changes in stability? <u>not understood</u>
- <u>≤ 1300 rpm</u>: Typical knock/stability limit.
- <u>> 1300 rpm</u>: Limited by occasional near-misfire cycle, ~1 in 1000 ⇒ <u>not understood</u>
  - Remains stable as load increased, but frequency of near-misfires increases.
  - Much higher loads could be obtained, but risk high COV due to “bad” cycles.
- TE ~1.5 %-units higher with CR = 16 across speed sweep (not shown).

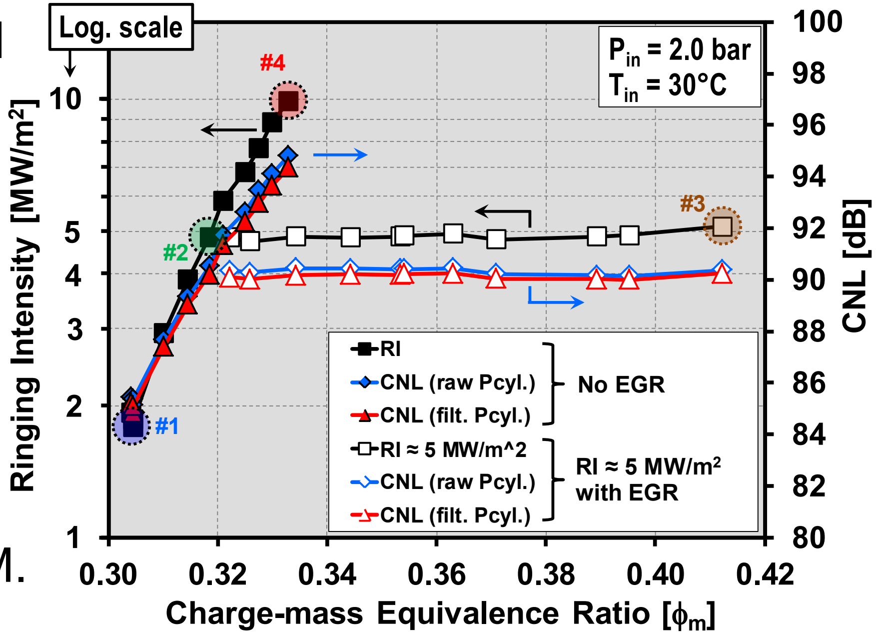
Premixed, P_{in} = 2.0 bar, T_{in} = 60°C, Ringing = 5

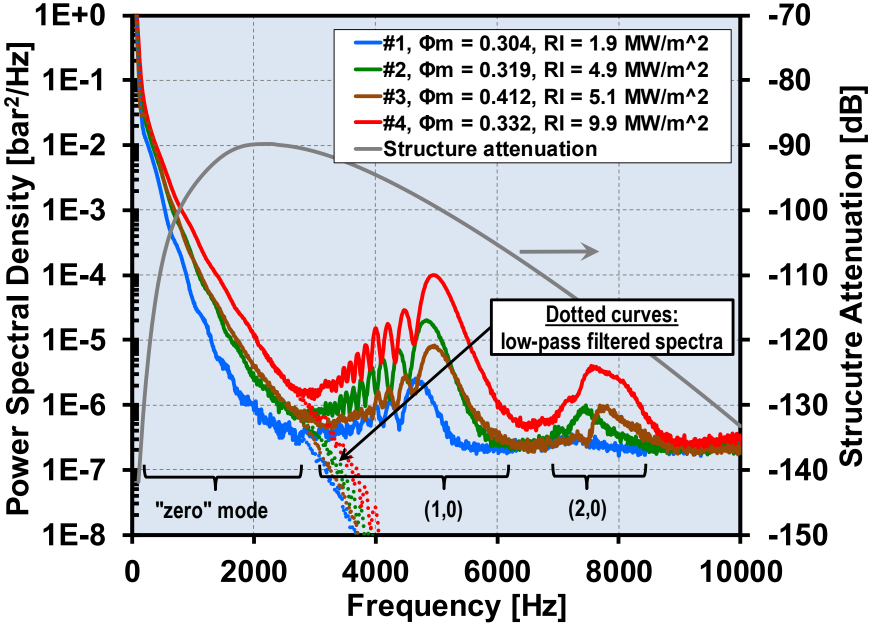




Analysis of Combustion Noise Level (CNL)

- Conducted extensive study of CNL and RI over range of loads, CA50, P_{in}, & speed.
  - Knocking and non-knocking conditions
  - Complete study in SAE 2014-01-1272.
- Example shows ϕ_m sweeps without (left) & with (right) CA50 ctrl to prevent knock.
- RI of 5 – 6 MW/m^2 correlates with onset of knock over wide range of conditions. $\Rightarrow$ RI eq'n accounts for effect of P_{in}, T_{in}, RPM.
- Here CNL = ~90 dB at knock onset, but different at other conditions (*e.g.* diff. P_{in}).
  - Spectral analysis shows CNL dominated by zero mode $\Rightarrow$ Press rise from combst.
  - CNL hardly affected by filter removing 1st and 2nd acoustically resonant modes.

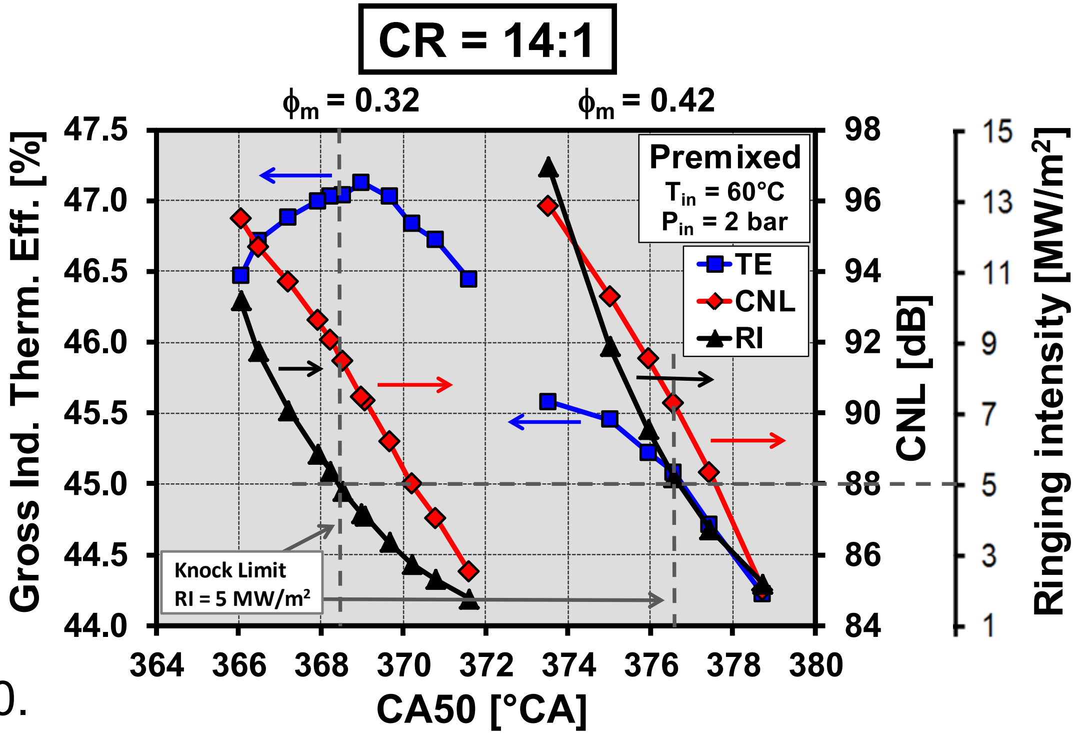




- **RI tracks resonant modes. $\Rightarrow$ Good for knock control. Poor for overall noise.**
- **CNL $\Rightarrow$ Good for determining noise from combustion event. Not sensitive to knock.**

Mitigating CNL with CA50 Retard

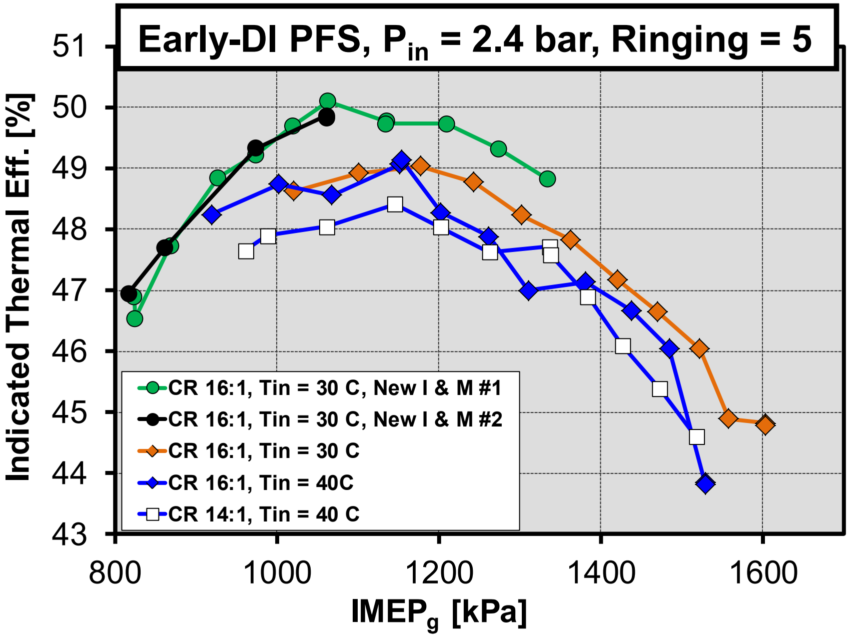
- CNL dominated by lower frequencies arising from the overall pressure rise with combustion. ⇒ CNL follows magnitude of PPRR (peak pressure-rise rate).
- CNL can be reduced by retarding CA50 to reduce PPRR ⇒ But also affects TE.
- For ϕ_m = 0.32, retarding CA50 from 366 to 372 CA reduces CNL from 96 to 85 dB.
  - TE increases until knocking gone, then decreases. ⇒ Only varies by about 0.6 %-units.
- For ϕ_m = 0.42, retarding CA50 from 373 to 379 CA reduces CNL from 96 to 85 dB.
  - TE falls by 1.4 %-units.
  - Falls monotonically since CA50 effect on TE larger for late CA50.

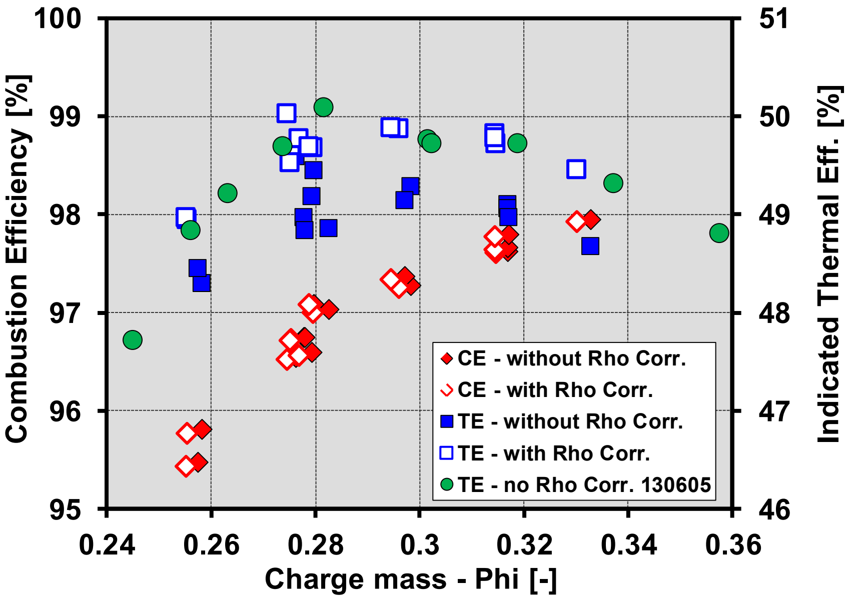


- Realistically, must keep RI ≤ 5 MW/m² to prevent knock, ⇒ very irritating sound.
  - For ϕ_m = 0.32, reducing CNL from 91.5 to 85 reduces TE by 0.6 or 0.7 %-units.
  - For ϕ_m = 0.42, reducing CNL from 90.3 to 85 reduces TE by 0.8 %-units.
- Significant noise (CNL) reduction can be achieved with minimal loss of TE.

Factors Affecting Thermal Eff. Measurement

- Previous work investigated how TE varies with operating conditions.
  ⇒ Seek conditions giving highest TE.
  - Obtained **max. TE = 49.2%**.
- Fueling measurement is also critical.
  - Use positive-displacement “Max” meter ⇒ Very high precision.
- Install new flow meter and re-calibrate (previous one was 11 years old).
- Discovered that Temp. variation in the lab can significantly affect fuel density ⇒ fuel measurement and TE.
  - Measure fuel temp. and correct.
  - Now data from hot & cool days match.
- Other problems identified and fixed
  - Seals in piston accumulator – fixed
  - Fuel volatility can affect gravimetric calib.
  - Compressibility differences between fuels.

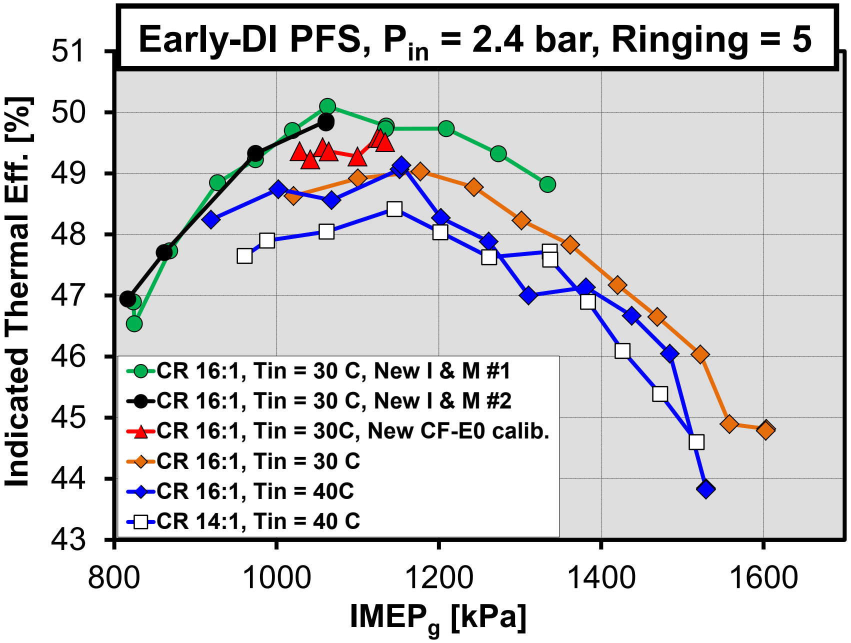


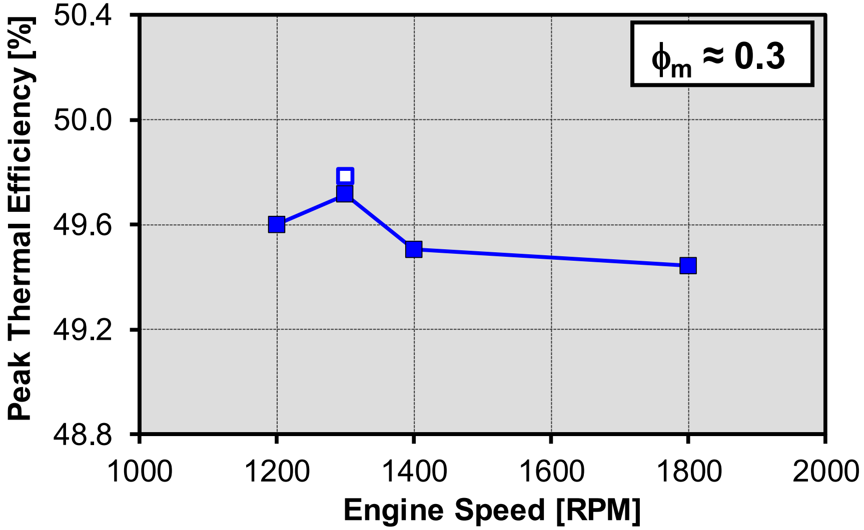


Peak Thermal Efficiency

- Applied all corrections and “fixes”.
- Re-calibrate using Cert. Fuel, same as experiments (no compressibility issues).
  - Resolved effect of volatility on calibration
- Installed a Coriolis meter as a check.
- **Peak T-E = 49.6%** for 1200 rpm.
  - Varies only weakly with load (ϕ_m) near the peak value.
- Engine speed has a small effect on the max. TE.
  - Slight overall trend of lower max. TE with increased speed.
  - **1300 rpm consistently gives a slightly higher TE.**

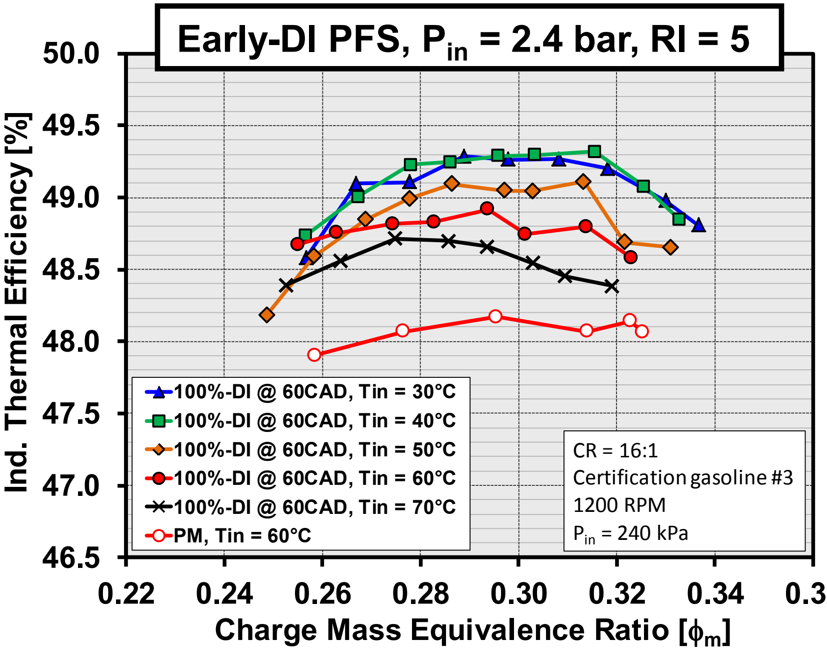
- **Best T-E ⇒ 49.7 – 49.8%**
  - CA50 = 366.3°CA, T_{peak} = 1511 K

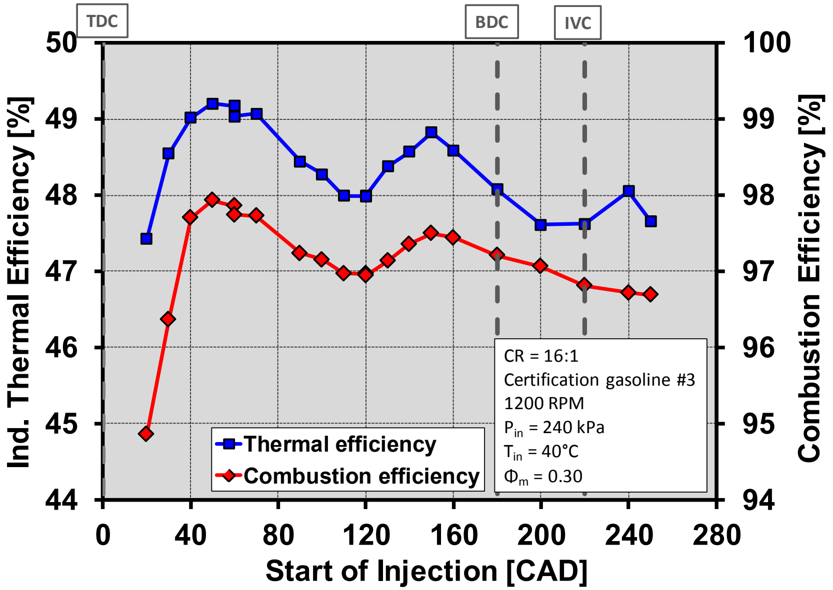




Optimization of PFS – Single Injection

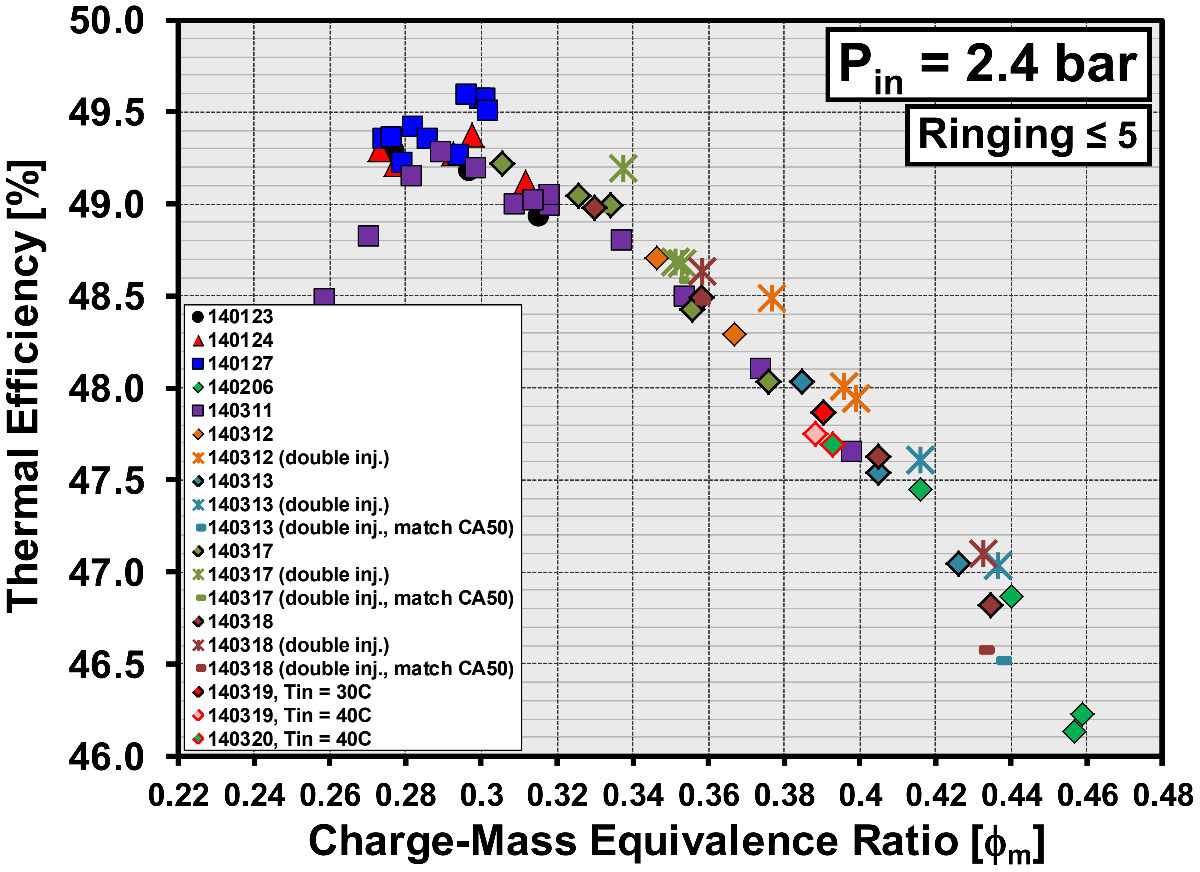
- Operating conditions for high TEs, with **single-injection early-DI PFS** have largely been optimized. However,
  1) Discrepancies found for optimal T_{in}.
  2) Effect of DI timing not fully explored.
- Conducted a well-controlled T_{in} sweep.
  - Vary ϕ_m at each T_{in} to find maximum TE.
- Very little difference, T_{in} = 30 or 40°C $\Rightarrow$ TE drops consistently for $T_{in} > 40°C$
  - TE for premixed lower than DI, same T_{in}.
- Optimal DI timing = 50 or 60° CA.
  - Confirms use of DI-60 (check over range)
- Combustion Eff. (CE) trends mirror TE.
  - Explains lower TE for DI-timing ≤ 40° CA.
  - Explains only about half of TE variation for DI-timing ≥ 70° CA.
    $\Rightarrow$ Cause of rest not yet understood.





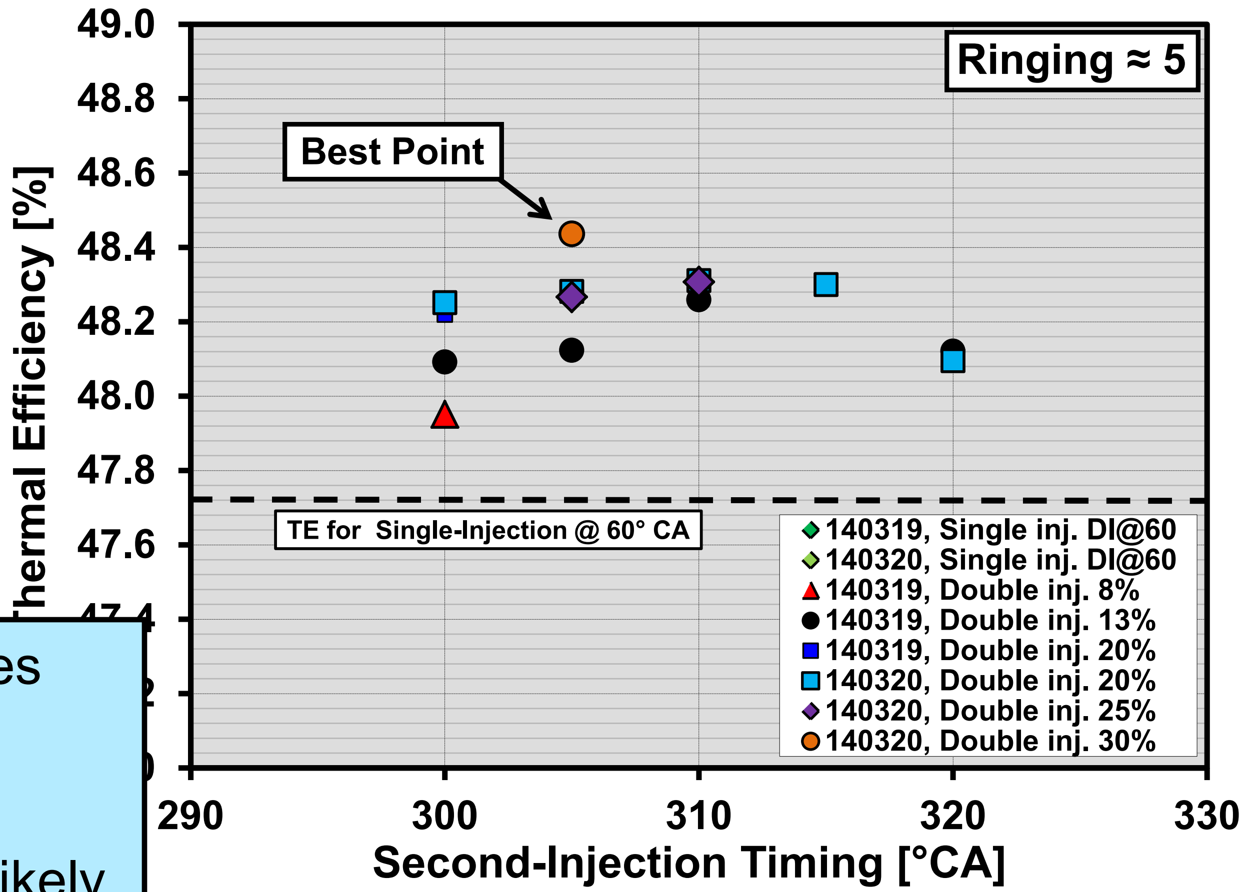
Potential of Double-Injection PFS to Increase TE

- Single-injection DI @ 60° CA shows typical trend of TE with φm.
  - Repeatability ~ 0.1 %-units for $0.33 \leq \phi_m \leq 0.44$
- Preliminary analysis of ϕ_m-distribution images indicates mixture not optimal.
- Double-injection DI using 92.5% @ 60° CA + 7.5% @ 320° CA.
  ⇒ Increases TE by ~0.2 -0.3 %-units over most of ϕ_m range.
- Gain is mainly due to more advanced CA50 for RI = 5 MW/m^2.
  - Improved PFS w/ double injection reduces HRR.
- Double-injections can better-optimize PFS & ⇒ increase TE.
- Can TE be increased further with additional stratification?



Initial Exploration of Increased Stratification

- Increase late-DI fraction and vary late-DI timing ⇒ use T_{in} = 40°C for better temperature control.
- Significant improvements possible ⇒ increase TE up to 0.72 %-units over single-injection vs. only 0.25 %-units for dataset on previous slide.
- Amplify scale to better see trends.
- Second-inj. timings of 310 - 315° CA appear to be best.
- Larger DI fraction sometimes better, but not always.
  - Further study required.



- This initial work indicates ⇒ Double-injections have strong potential.
- Further improvements likely.

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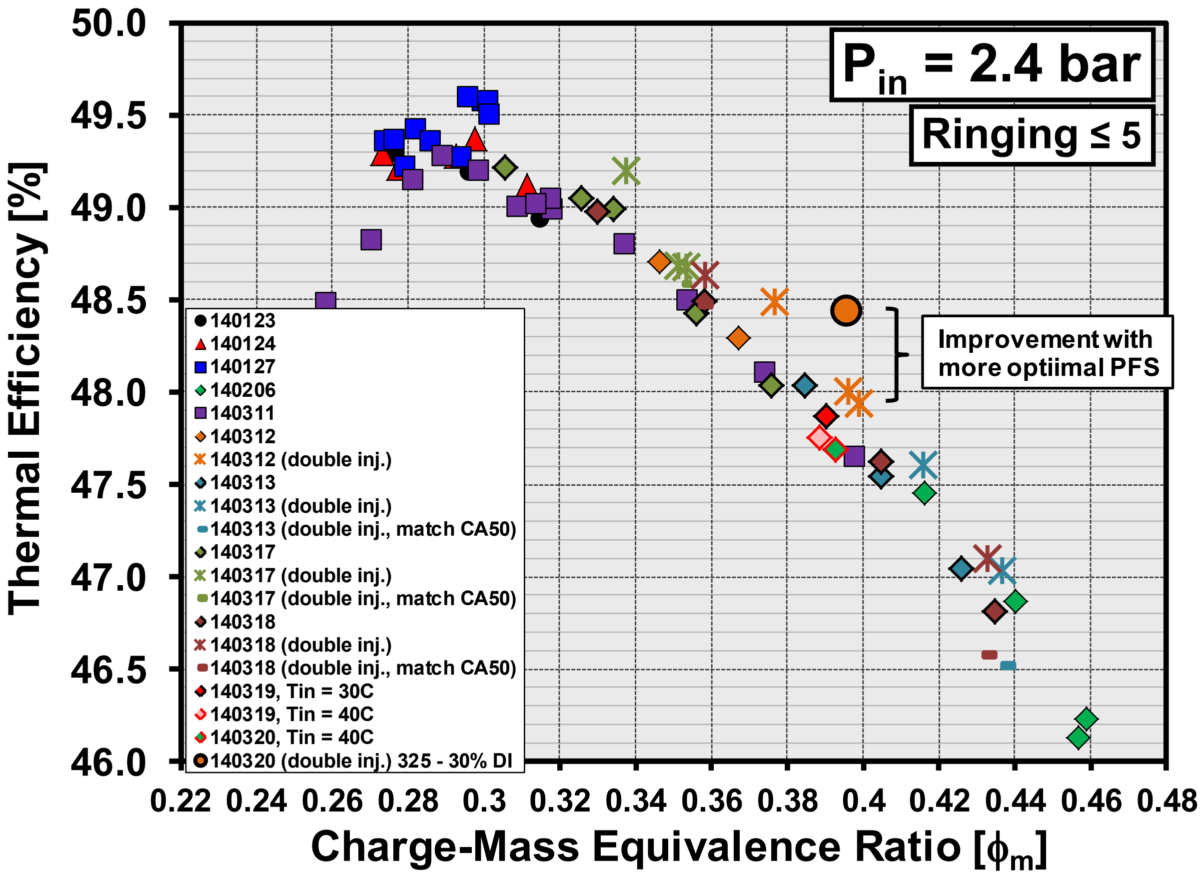
- Double-injection can better-optimize PFS & ⇒ increase TE.
- Can TE be increased further with additional stratification?
- **Yes!**



Response to Reviewer Comments

1. **Reviewers made many positive comments.** ⇒ We thank the reviewers.
2. **Knocking limit might not be Noise limit. What is the sensitivity of TE to noise reduction below the CNL at the knock limit, by further retarding CA50?**
   - Examined this, and the results on slide 12 show that CNL can be reduced significantly for a fairly modest reduction in TE. ⇒ Sensitivity $\Delta TE / \Delta CNL \approx 0.8$ %-units / 5 dB.
   - Improved PFS could reduce TE loss for controlling noise.
3. **Requested more information on planned intake-port revisions & effect on TE.**
   - Current head designed for SR = 2.3. We use an anti-swirl plate in one port to reduce to SR = 0.9, which might generate additional turbulence and increase heat transfer.
   - Cummins now makes a head with port geometry directly giving SR = 0.7. These heads are being used for the facility upgrade for spark-assist capability and 300 bar GDI.
4. **There were several questions/comments on the need to better understand the relationship of our peak TE to those of other LTC engines & to conv. diesel.**
   - As shown on slides 13 and 14, we have reworked our fuel measurement, and better optimized operating conds. Peak indicated TE is now 49.8 vs. 49.2% reported last year.
   - These are the highest known efficiencies reported for mostly premixed LTGC.
   - Peak TE for RCCI & CDC vary with publication. Most recent information from UW shows: H-Duty 54.3%, L-Duty 49% for RCCI and H-D 48.7%, L-D 45% for CDC (no aftertreatment).
   - Our engine is intermediate size ⇒ peak TE is above L-D RCCI and only ~1 %-unit below an RCCI TE scaled to our engine size. It is well above CDC. ⇒ Will study heat transfer, etc.
   - Achieved loads to 19.4 bar $IMEP_g$ with gasoline vs. ~15 bar $IMEP_g$ for RCCI with gasoline.

Collaborations

- Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) / HCCI Working Group, under a memorandum of understanding (MOU).
  - Twelve OEMs, Three energy companies, Six national labs, & Several universities.
- General Motors: Bimonthly internet meetings ⇒ in-depth discussions.
  - Provide data to GM on boosted LTGC and for modeling PFS-LTGC.
- Cummins, Inc.: Design & fabrication of low-swirl, spark-plug cylinder heads.
- LLNL: Support the development and validation of a chemical-kinetic mechanism for gasoline/ethanol blends, Pitz *et al*.
- U. of California - Berkeley: Collaborate on CFD modeling of PFS-LTGC.
- U. of Melbourne, Australia: Collaborate on biofuels work & kinetic modeling.
- Chevron: **Funds-In project** on advanced petroleum-based fuels for LTGC.

Future Work

Improved PFS-LTGC (multi-year task)

- Continue investigation of multiple injections to better optimize fuel distributions for PFS-LTGC.
  - Improvement of TE over the load range.
  - Potential for extending the high-load limits at various P_{in}.
- Image fuel distributions in optical engine to guide fuel-injection strategies.
- Guidance from CFD modeling at UC-Berkeley and GM.

New Cylinder Head

- Compare TE, load range, heat transfer, etc. ⇒ effect of new low-swirl ports.
- Potential of 300 bar GDI injector for PFS improvements.
- Initial testing of spark-assisted LTGC.

Analysis

- Use turbo-charger and friction models from GM to investigate how these real-engine effects would change LTGC performance.

Support of LTGC/HCCI Modeling

- Continue to provide data, analysis, and discussions to support: 1) kinetic modeling at LLNL, and 2) CFD modeling at UC-Berkeley and GM.

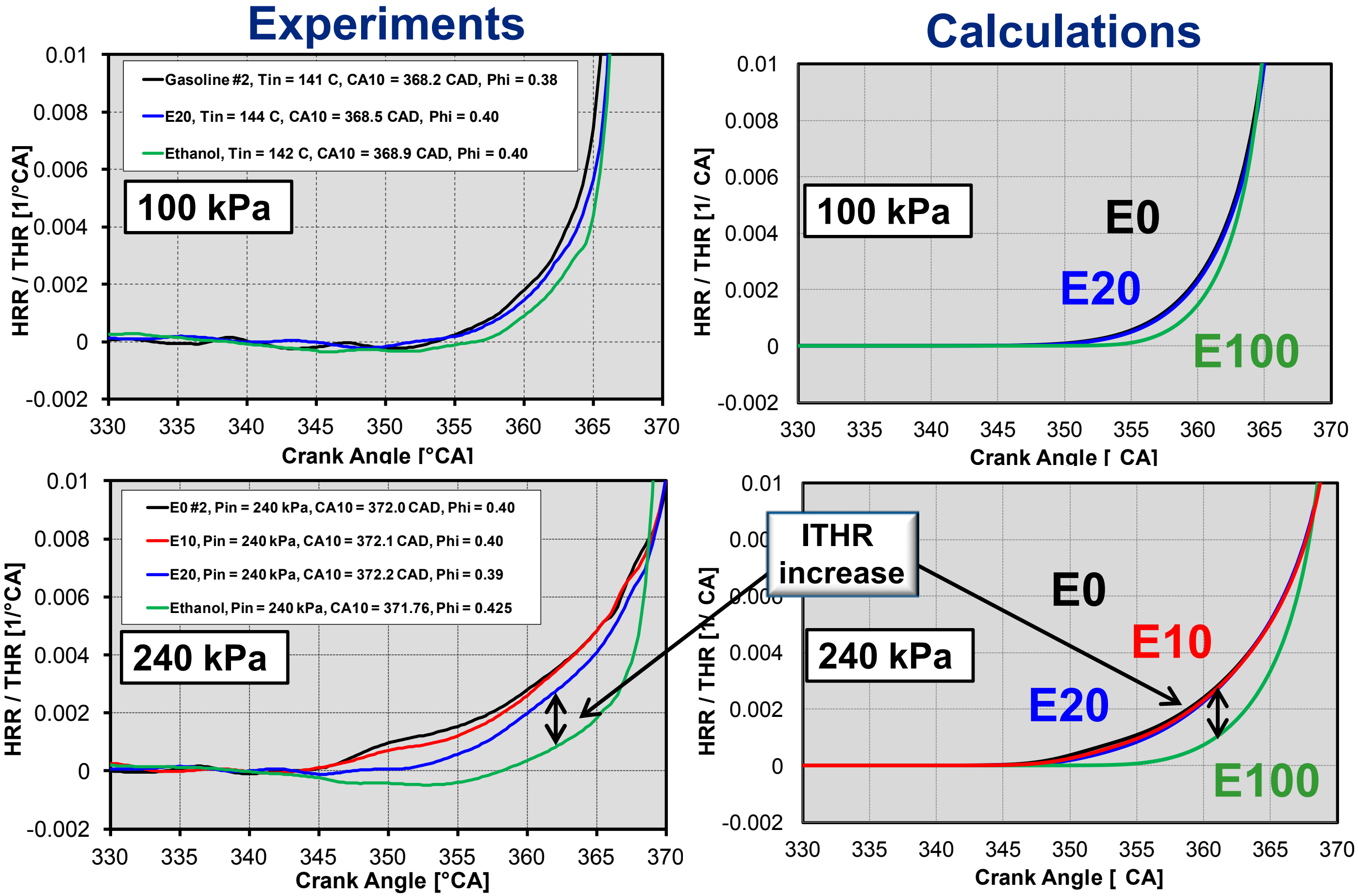
Summary

- Determined the high-load limits for CR =16 for both Early-DI-PFS and premixed fueling over a wide range of P_{in} and engine speeds.
  - Max. loads ≥ CR 14 for $P_{in} < 2.5$ bar. ⇒ **16 bar IMEP_g with P_{in} of only 2.4 bar**.
  - High req'd EGR limits O_2 at high boost. **Max. load 17.7 bar vs. 19.4 for CR 14.**
  - Miller cycle shows little potential benefit ⇒ slightly increases load at highest P_{in}.
  - Determined load limit for speeds from 1000 – 2200 rpm. ⇒ Discovered that above 1300 rpm, load limited by intermittent partial misfire, a new type of limit.
- Conducted extensive study of CNL and RI over a range of loads, CA50, P_{in}, speed & knock intensity. ⇒ Showed CNL is not sensitive to knock.
  - RI tracks resonant modes (knock). ⇒ CNL gives combustion noise, not knock.
  - Showed CNL reduced significantly by CA50 retard with only a small loss of TE.
- Analyzed and reworked our fuel measurement system and better optimized operating conditions. **Peak indicated TE is now 49.8%** vs. 49.2% in FY13.
- Well-controlled studies showed the effects of T_{in}, DI-timing, & speed on TE.
- Initial investigation of double-injection DI-fueling showed that it can significantly improve PFS to increase the TE over the load range.
- Collaborated with chemical-kinetic modelers at LLNL on gasoline/ethanol blends, and with CFD modelers at UC-B & GM ⇒ see Technical B-up Slides

Technical Backup Slides

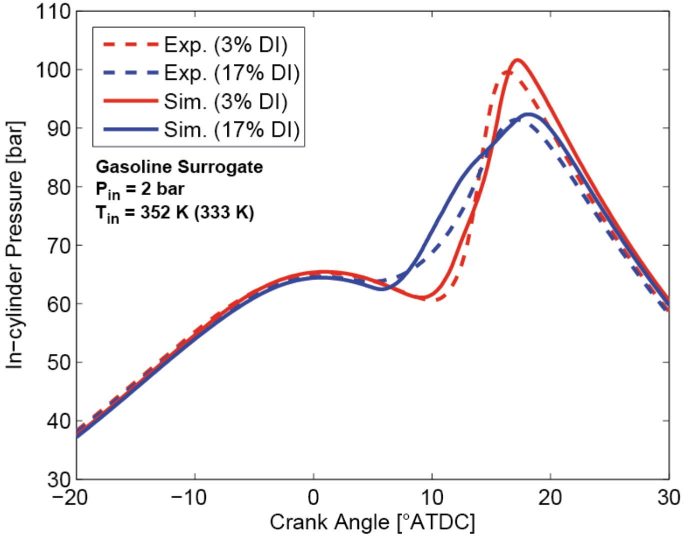
LLNL Collaboration – Kinetic Modeling

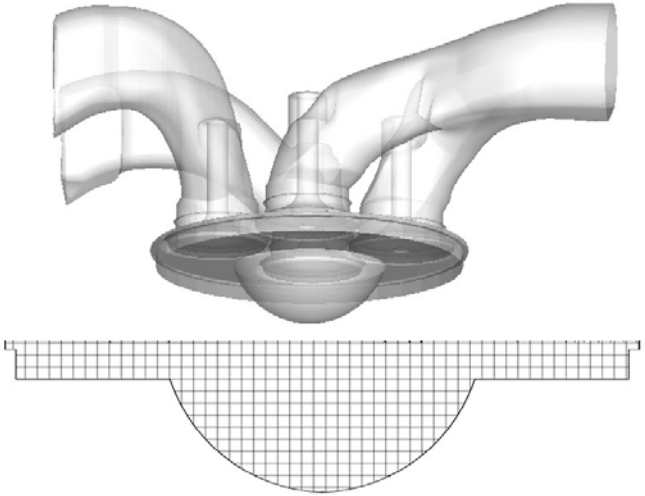
- In FY13, showed that gasoline/ethanol blends work well for LTGC.
- Showed the importance of intermediate temperature heat release (ITHR) and the increase in ITHR with boost for stable high-load operation.
- Work with LLNL (Pitz *et al.*) to help them develop and validate kinetic models for gasoline/ethanol blends that work for LTGC and capture trends in ITHR.
- P_{in} = 100: good agreement.
- P_{in} = 240: captures overall ITHR increase with P_{in}.
- Additional work needed to capture small differences between E0, E10, and E20.



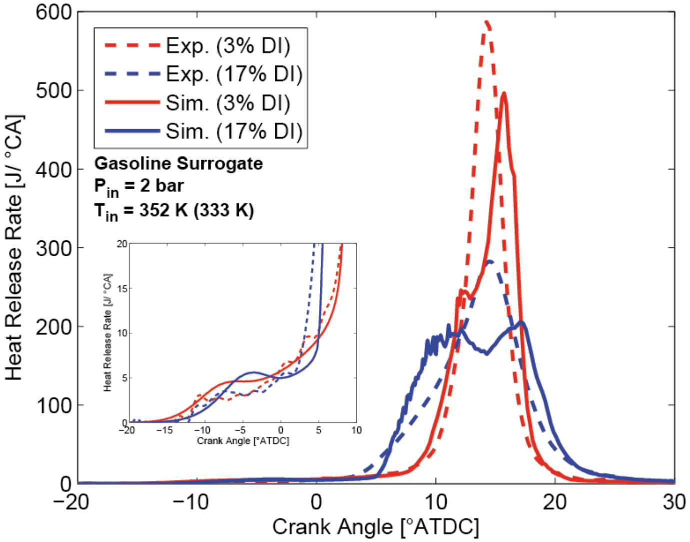
UC-Berkeley Collaboration – CFD Modeling

- Work with Ben Wolk and J-Y Chen at UC-Berkeley to investigate whether CFD models can capture the effects of PFS? (UC-B funding from DOE-NSF grant.)
  - Explained PFS and our data showing how it works.
  - Supplied data and engine geometry models.
  - Discussion and feedback for improvement.
- Initial results from UC-B capture the reduction in HRR and PPRR with PFS.
  ⇒ Refinement needed to better match spread of heat release with PFS.





Grid of the Sandia-LTGC Engine for use with CONVERGEÊ CFD software



Effect of Miller Cycle ⇒ CR = 14, ER = 16

- For CR16, more EGR is required to limit the CA50 advance with boost.
  ⇒ Limits air, reducing max. load (ϕ_m).
- Would a Miller cycle be better?
  - Reduce req'd EGR & allow higher ϕ_m.
  - But it would reduce the charge mass.
- Trade-off ⇒ Which wins?
- Compute max. IMEP_g assuming a charge-mass reduction of 12.5% compared to CR = ER =14.
  ⇒ Incr. load to account for higher TE.
- For $P_{in} \le 3.0$ bar, higher loads with std. cycle, CR = 16 ⇒ **Max IMEP_g = 15 bar.**
- For $3.2 \le P_{in} \le 3.4$ bar, higher loads with Miller cycle ⇒ **Max IMEP_g = 15.7 bar, a marginal increase.**

- **Standard cycle seems better overall.**