Project purpose: to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical HCCI and HCCI-like engines by industry.

- HCCI has substantial advantages over traditional engines.
  - Compared to SI engines ⇒ fuel consumption reduced up to 30%.
  - Compared to Diesel ⇒ meet 2010 without lean-NO\textsubscript{X} or PM aftertreatment, and with similar efficiency.

- Huge potential for reducing US petroleum consumption, 2 – 3 MBPD.

- HCCI engines can operate with alternative fuels ⇒ further reductions.

- HCCI engines are potentially lower cost than a diesel, with similar eff.

- Research is required to overcome the technical barriers.
Response to Previous Reviewer’s Comments

- Reviewer’s comments were generally very positive.

- No strong consensus on comments/suggestions.
  - Expressed importance of working with two-stage ignition fuels.
    > We will continue to include two-stage fuels in our investigations.
    > Conducting substantial work in this area under Aramco/Chevron-funded complementary project. ⇒ Results presented at AEC meetings & SAE.
  - Importance of VVA for studying NVO, etc. ⇒ System is now operational.
  - Importance of industrial interactions.
    > We are working to maintain/expand our interactions, but keep work broad enough to be valuable to all interested in HCCI & HCCI-like combustion.
    > Discussion of industrial interactions will be given later in Technology Transfer slide.
Technical Barriers

Our work in FY08 addresses the following barriers:

- Extend HCCI operating range to higher loads.
- Control HC and CO emissions at low loads.
- Improved understanding of fuel effects.
- Control of combustion phasing over the load/speed map.
Approach

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

- Metal engine ⇒ design well-characterized experiments to isolate specific aspects of HCCI/SCCI combustion & relationships between parameters.
  - Many fundamentals are also relevant to HCCI-like diesel, e.g., EGR effects.

- Optical engine ⇒ detailed investigations of in-cylinder processes.
  - Laser-sheet imaging of temperature distribution.

- Computational Modeling ⇒ supplement experiments by showing cause-and-effect relationships that are not easily measured.
  - In-house CHEMKIN (Senkin) single- and multi-zone kinetic modeling.
  - Collaborate with LLNL & UW on full KIVA/multi-zone simulations.

- Combination of techniques provides a more complete understanding.

- Transfer results to industry.
Matching all-metal & optical HCCI research engines.
- Single-cylinder conversion from Cummins B-series diesel.

Cooled EGR loop added for current experiments.
Technical Accomplishments – FY08

- Completed investigation of high-load limits for single- and two-stage fuels and identified three different mechanisms for these limits.

- Determined the effect of EGR/residuals on the HCCI heat-release rates and $\text{NO}_x$ formation for well-mixed HCCI.
  - Isolated these effects from EGR effects on combustion phasing and IMEP.

- Initiated development of a planar temperature-measurement technique to determine the evolution of thermal stratification in an HCCI engine.

- Completed detailed exhaust-speciation analysis for iso-octane fueling.
  - Expanded study to include exhaust-speciation for gasoline fueling.
  - Project conducted in cooperation with LLNL.

- Completed VVA system – demonstrated NVO and late IVC operation.

- Supported chemical-kinetic and CFD modeling work at LLNL & UW.
  - Kinetic mechanisms $\Rightarrow$ improve pressure dependence, for various fuels.
  - CFD modeling $\Rightarrow$ better understand in-cyl. processes & emiss. formation.
To prevent knock, combustion phasing must be retarded as fueling is increased.

Iso-octane (1-stage ignit.) much more sensitive to changes in $T_{in}$ at high retard.
- Wall-heating feedback limits CA50 control at IMEPg = 486 or 520 kPa.
- CR=14, NO$_X$ > 2010 limits.

PRF80 & PRF60 (2-stage), less sensitive to $T_{in}$, allows greater retard & higher IMEP.
- NO$_X$ < 2010 limits, because $T_{in}$ is lower, so lower peak temp. and more induced mass.

PRF80 limited to IMEPg = 650 kPa, due to NO$_X$ feedback runaway.

PRF60 limited to IMEPg = 640 kPa, due to insufficient O$_2$, because of high EGR levels required to maintain phasing retard.

Details in SAE 2008-01-0054
Can EGR help to avoid load-limit factors on previous slide? \(\Rightarrow\) Reduce knock and \(\text{NO}_x\) with less timing retard.

- Knock results from excessive PRR/HRR.

Previous works have suggested that EGR is effective for reducing the HRR and \(\text{NO}_x\) formation (peak temps.).

However, results not conclusive since other effects of EGR were not controlled.

- Combustion phasing (CA50) & IMEP.

EGR retards CA50, which slows PRR.

- Similar results obtained with reduced \(T_{\text{in}}\).

With phasing control, the effect on HRR is unclear for low EGR levels (12%).

Conducted well-controlled experiments over wide range of EGR levels.
Maintain constant CA50 = 370°CA by increasing $T_{in}$ as EGR is added.

Plot shows ~47% EGR ⇒ $T_{in}$ was increased from 142°C to 176°C.

Higher $T_{in}$ reduces charge mass.

- Same C/F ratio gives lower IMEP.
- Constant fueling also gives lower IMEP.

Must increase fueling to maintain constant IMEP with EGR addition.

- Lower $\gamma$ ($c_p/c_v$) with EGR reduces $\eta_{thermal}$

Gasoline, CA50 = 370°CA

Effects of EGR on IMEP and Thermal Efficiency

- Base Cond: 0% EGR
  - $\phi = 0.42$, $T_{in}=142°C$
  - PRR = 5 bar/°CA

- $T_{in} = 176°C$ with EGR

- Increasing EGR
  - Lower $\gamma$ ($c_p/c_v$) with EGR reduces $\eta_{thermal}$
Max. PRR for constant IMEP reduced slightly from 5 to 4.5 bar/deg with EGR. ⇒ Incr. IMEP 450 to 475 kPa, same PRR.

Very small benefit. ⇒ Similar result achieved by retarding CA50 only 1°CA.

Loss of thermal eff. ~2% using EGR compared to ~0.1% for retard.

Peak temperatures and NO\textsubscript{X} increase!
- Higher $T_{\text{in}}$ and higher required fueling.
- Slightly less increase as approach stoich.

EGR gives minimal direct benefit for PRR & is detrimental for $\eta_{\text{th}}$ & NO\textsubscript{X} at cond. st’d.

However, often needed for ignit. control and allows stoich. op. ⇒ 3-way catalyst.

Limits peak temps. for SCCI/PCCI comb.
Thermal stratification (TS) is essential for HCCI operation at all but the lowest loads.  
- Amplify effect with timing retard for high load.

Previous work ⇒ TS caused by convection of cooler near-wall gases into bulk gas.

Increasing TS has strong potential for extending high-load limit of HCCI.

Measuring in-cyl. temperatures is critical for understanding TS, and ways to increase it.

PLIF of toluene tracer is temp. sensitive.  
- For well-mixed fueling, variations in PLIF intensity correspond to variations in temp.  
- Calibrate temp. sensitivity in-cylinder.

Preliminary images very promising ⇒ detect increase of TS from 305° to 360°CA.

Studies of development of TS are planned.
Joint project with LLNL. ⇒ They will discuss gas-spec. analysis techniques.

Fueling- and stratification (SOI)-sweeps show similar trends for both fuels.
- Confirms significant OHC in emissions. (formaldehyde, acetaldehyde, acetone, etc.)
- Unreacted fuel most significant HC spec.

Normalized data shows progression from:
- fuel → break-down prod. → small spec. → CO.
  - Explained by in-cyl. temp. distribution.
  - Indicates where various species form in-cyl.

SOI-sweep indicates two reasons for improved low-load $\eta_{comb}$ with stratification.
- Locally richer regions burn more completely.
- Reduced mixing time removes fuel from crevice and colder near-wall regions.

Details in SAE 2008-01-0053
VVA System is Operational

- Electro-hydraulic VVA is fully flexible.
  - Control of valve timing, duration, and lift.

- Design by International Truck & Engine Co., adapted to fit our engine.
  - In-house developed electronics and software.

- VVA build complete. \( \Rightarrow \) Verified VVA capability for late IVC and NVO operation on motored engine.

- Allows investigation of exhaust rebreathe and NVO, vs. heated \( T_{\text{in}} \).
  - Strong interest by auto companies.

- Late IVC allows variation of effective CR for ctrl., & high-CN fuels (D2-like).
Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) Working Group.
⇒ Discussion and feedback incorporated into work.

- **OEM Partners:** Caterpillar, Chrysler, Cummins, Detroit Diesel, Ford, GE, GM, International, John Deere, and Mack-Volvo.
- **Energy Co. Partners:** BP, Chevron, ConocoPhillips, ExxonMobil, and Shell.
- **National Lab. & Univ.:** SNL, LANL, LLNL, ANL, and U. Wisconsin.

- Participate in meetings of the University HCCI Consortia (UM & UW).

- **GM:** In-depth discussions on gasoline HCCI. ⇒ Led to current EGR-HRR study. Suggested future work on exhaust-rebreathe HCCI & thermal strat.

- **International Truck & Engine Co.:** Development of VVA system. Discussions to provide guidance and review of their diesel-HCCI project.

- **Saudi-Aramco:** Funding complementary project on advanced HCCI fuels. **Chevron:** Joined Aramco project as equal partner (3-yr contract in place).

- **LLNL & Universities:** Cooperative modeling, diagnostic, & emiss. projects. ⇒ Details on next slide.
Interactions with LLNL and Universities

- **LLNL**: 1) Support chemical-kinetic mechanism development, Pitz et al.  
  2) Cooperative project for detailed exhaust speciation, Davisson et al.

- **LLNL and Univ. of Wisconsin**: Cooperative Project on CFD modeling of in-cylinder processes and emissions formation, Aceves et al. LLNL, Hessel and Foster, UW.

- **Stanford**: Advanced two-laser optical diagnostic for planar for in-cylinder temperature and mixture measurements, with R. Steeper, SNL (Hansen et al., Stanford).

- **Univ. of Wisconsin – Milwaukee**: Data for modeling effort.

- **Univ. of New South Wales, Australia**: Discussions regarding potential collaboration on modeling of ethanol-fueled HCCI.
Plans for Next Fiscal Year

- Complete investigation of the effects of EGR/residuals on HRR and NO\textsubscript{X}, by extending operation to the high-load limit of HCCI.
  - Can higher IMEP be reached with EGR at T\textsubscript{wall} control limit? (\(\eta\)\textsubscript{thermal} and NO\textsubscript{X}?)
  - Future direction: investigate benefits of EGR for boosted operation.

- Investigate development of thermal stratification through the cycle using current single-laser planar temperature technique (bulk-gas and BL).
  - Future direction: extend to other op. cond., e.g. variations in speed, piston geom.
  - Future direction: compare with Stanford 2-laser tech. & apply to high-resid. cond.

- Apply VVA to compare HRR and performance for exhaust rebreathe, NVO, and heated T\textsubscript{in}. ⇒ Understand effects on thermal stratification & load limits.
  - Future direction: Initial focus on exhaust rebreathe, based on disc. with OEMs.

- Investigate Ethanol ⇒ effects of load, speed, EGR, and other parameters.
  - Future direction: mixture-stratified operation with ethanol (other renewable fuels).

- Detailed exhaust speciation under near-misfire conds. for 1- & 2-stage fuels.

- Continue to collaborate with LLNL on improving chemical-kinetic mechanisms and on CFD/kinetic modeling.
Summary and Conclusions

- Three mechanisms identified that limit high-load HCCI operation for various fuels/conditions: 1) wall-heating feedback ⇒ thermal runaway, 2) NO\textsubscript{X} feedback runaway, and 3) limited O\textsubscript{2} due to high EGR.

- EGR gives little direct benefit for slowing HRR and reduces $\eta_{\text{thermal}} \sim 2\%$.
  - Similar benefit achieved by retarding CA50 only 1°CA, reduces $\eta_{\text{thermal}} \sim 0.1\%$.

- For well-mixed operation, EGR results in higher NO\textsubscript{X} for same IMEP.
  - However, stoichiometric operation with high EGR allows use of 3-way catalyst.

- Developed planar temperature-measurement technique ⇒ based on PLIF imaging of fuel-tracer, calibrated in-cylinder.
  - Demonstrated measurement of thermal stratification.

- Detailed exhaust speciation study for iso-octane and gasoline.
  - Identified main HC & OHC species, and likely in-cyl. location for their formation.

- VVA system is operational – demonstrated NVO and late IVC operation.
Publications, etc.


Invited Presentations
