Light-Duty Diesel Combustion

Light-Duty Engine Experiments

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Light-Duty Combustion Modeling

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Project ID: ACE002

Overview

Timeline:

- Project started in 1997 to support DOE/industry advanced engine development projects
- Continuous evaluation of direction through industry feedback

Budget:

- Funded by DOE on a year-by-year basis
  - SNL: $544k
    - PI, post-doc, technologists, op. costs
  - UW: $99k subcontract
    - 50% post-doc

VT program: barriers addressed

A: Lack of fundamental knowledge of advanced engine combustion regimes

B, G: Lack of cost-effective emission control

C: Lack of modeling capability for combustion and emission control

VT program: technical targets addressed

- 40% fuel economy improvement over 2009 baseline gasoline vehicle
- Tier 2, bin 2 emissions
- Emission control efficiency penalty <1%
- Specific cost: $30/kW

Partners:

- Close collaboration with GM and Ford diesel R&D groups within the Advanced Engine Combustion MOU
- Vigorous collaboration between SNL / Convergent Science / GM
- Collaboration with ORNL (ACE016) / Delphi

Technical / Programmatic Approach

- **Develop and disseminate fundamental understanding of advanced combustion processes**
- **Evaluate and improve computational modeling capabilities**

» Common engine platform (GM 1.9L head)
» SNL provides optical data, UW provides simulation results
» Regular emails and teleconferences

Subcontract with UW: CFD Simulation
- Model development; optimization methods
- 3D-CFD simluation results complement experimental data
- ***Supplemental insight beyond exp. data***

» Regular teleconferences and meetings with GM and Ford R&D
» Involvement with decisions regarding UW's efforts
» Interaction with other AEC MOU partners at AEC working meetings

AEC MOU Industry Partners
- Direct link to the needs of industry
- ***Crucial support, feedback, suggestions***

SNL: Optical Engine Experiments
- GM 1.9 L cylinder head
- Measurements: flow, mixture formation, ignition, combustion, species
- ***Detailed analysis and result synthesis***

Convergent Science (Third-Party)
- Commercial code vendor
- Evaluation of code, establishment of best practices for engine cycle simulations
- ***Direct interface with many OEMS: getting technological insights into the market***

» CSI - GM - SNL cooperation
» SNL provides optical data; CSI uses GM 1.9L grid
» Regular e-mails & teleconferences, planned joint publications

Other National Labs (ORNL, Argonne)
- Scott Curran, ACE016; Chris Powell, ACE010
- Secured state-of-the-art fuel injectors from Delphi for use at SNL, ORNL, and ANL
- Close-coupled pilot injections: injector dynamics, noise, emissions, efficiency,
- **Leverage capabilities of each facility**

» Planned cooperative experimental campaigns

Milestones / Progress

- SNL: experimental work
  - **Piston bowl geometry:** in-cylinder flow, effects on engine efficiency and emissions
  - Unplanned overhaul of CLR base engine (sliding surfaces worn out after 17 years of operation)
- SNL: analyses
  - **Piston bowl geometry**: impact on in-cylinder flow
  - Effect of pilot injections on main ignition processes and **late-cycle flow behavior**
- UW: computational simulations and analyses
  - **Converged CFD solution** (RANS) matches experimentally-determined flow structure
  - **Piston bowl geometry**: differences in squish-swirl interactions

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<tr><th colspan="2"></th><th colspan="10">2015</th><th colspan="3">2016</th></tr>
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<tr><td rowspan="2">SNL</td><td>Experimental work</td><td>Finish swirl plane PIV</td><td colspan="2">High speed OH*/NL imaging for GM</td><td>Optical setup; piston failure</td><td colspan="3">Reconfigure lab for metal engine testing; repair emissions equipment; bowl geometry scoping study</td><td colspan="5">CLR base engine: problem diagnosis; complete rebuild; reassembly of optical engine; break-in and commissioning</td><td>Fuel tracer PLIF</td></tr>
<tr><td>Analyses</td><td colspan="3">Process swirl plane PIV data: stepped-lip piston bowl</td><td colspan="4">Develop combustion image velocimetry (CIV) technique; apply to pilot-main dwell sweep</td><td colspan="4">Analysis of piston bowl geometry scoping study: efficiency and emissions trends; CDC and LTC</td><td>Publish CIV, PIV</td><td>GT-Power setup - PLIF study</td></tr>
<tr><td>UW</td><td>CFD Simulation</td><td colspan="10">First complete release of "FRESCO" CFD platform: rezoning algorithm, implementation of polymorphic field structures; vector and tensor algebra; adaptation of libraries for parallel flow solver; improvement of parallel computational efficiency; debugging; benchmarking against existing KIVA simulations</td><td colspan="3">Cold flow bowl geometry study, comparison with swirl plane PIV</td></tr>
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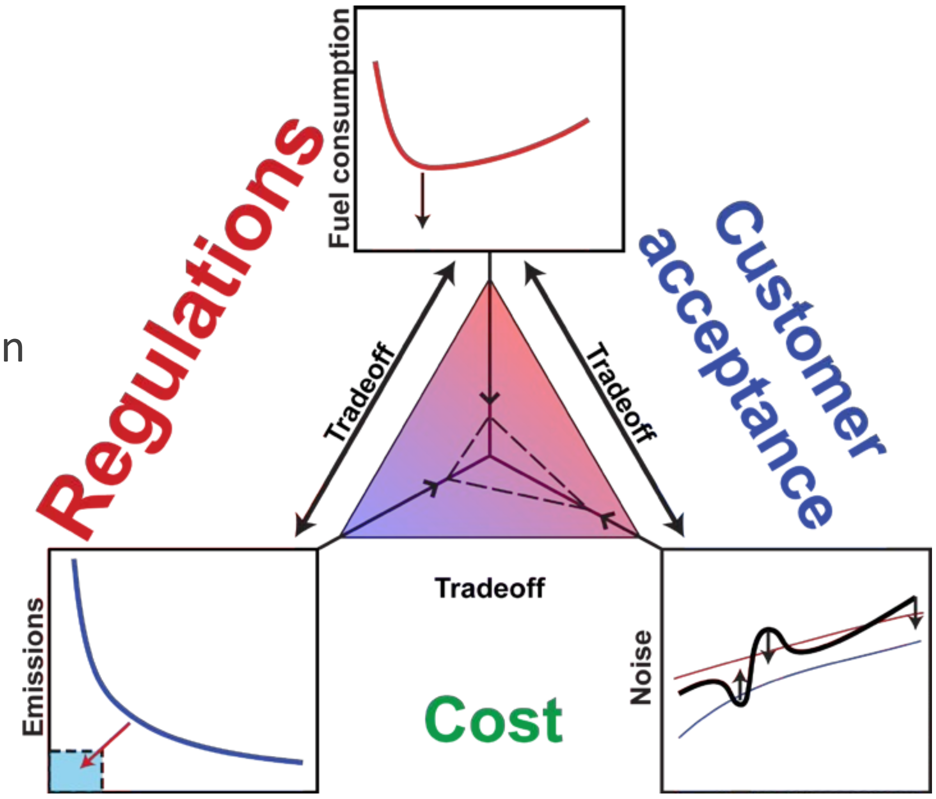
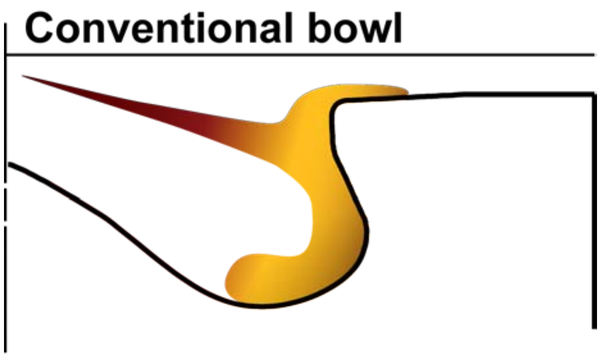
Relevance of light-duty diesel research

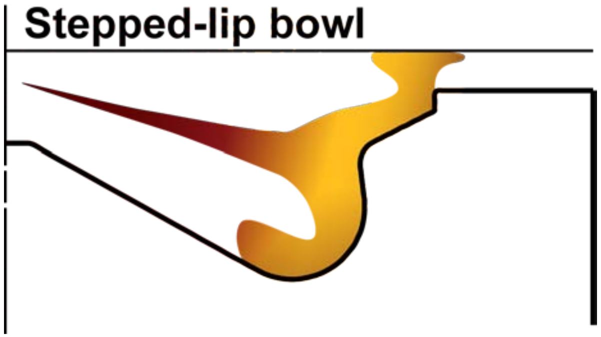
- **In order for light-duty diesels to help meet future CAFE standards, challenging tradeoffs between efficiency, emissions, and noise must be overcome**
  - CAFE: estimated combined ~49 mpg for cars and light trucks by 2025[1]
    - ACEC tech team research targets: 20-25% BTE improvement by 2025
  - Emissions: extremely stringent Tier 3 standards phased in from 2017-2025[2]
  - Noise: critical for advanced combustion technologies to reach the market[3]
- Light- and medium duty diesel engine development requires a detailed understanding of how in-cylinder processes impact these tradeoffs
- More accurate predictive simulation capabilities will lead to improved combustion chamber designs



Piston bowl geometry: relevance for swirl-supported light- and medium-duty diesel engines

- **Stepped-lip bowls can be a cost-effective means to cleaner, more efficient diesel engines, but fundamental knowledge is lacking about how their advantages are realized and what their limitations and drawbacks are**
- These bowls are often used in medium-duty diesel engines and were recently introduced in light-duty diesels for several reasons:
  - Improved air utilization: reduced soot emissions[4, 5, 6]
  - Less soot-wall interaction: less wear/heat transfer[4, 5, 6]
  - Smaller surface area / reduced heat transfer[4, 5, 6, 7, 8]
  - Improved late-cycle mixing[6]; faster combustion rates[5, 6]
- Experiments (SNL) and 3D-CFD simulations (UW) are needed to provide insight into how piston geometry can impact mixture formation and late-cycle mixing in swirl-supported, direct injection engines



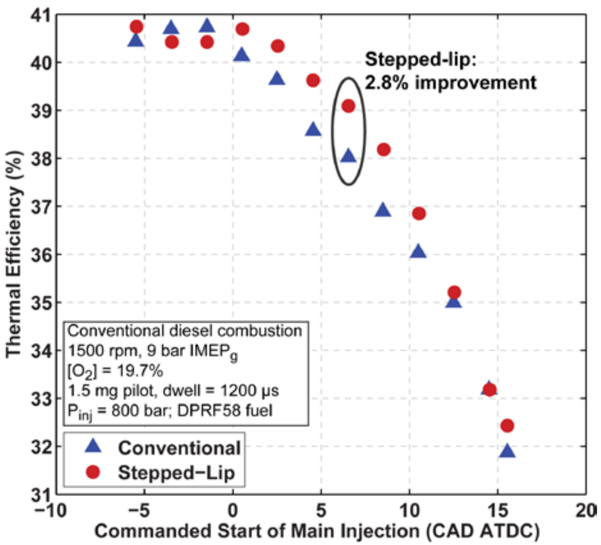


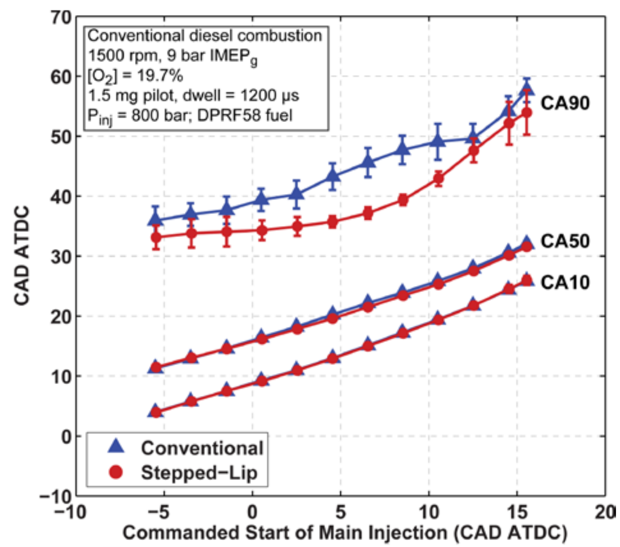
Relevance of pilot injection studies

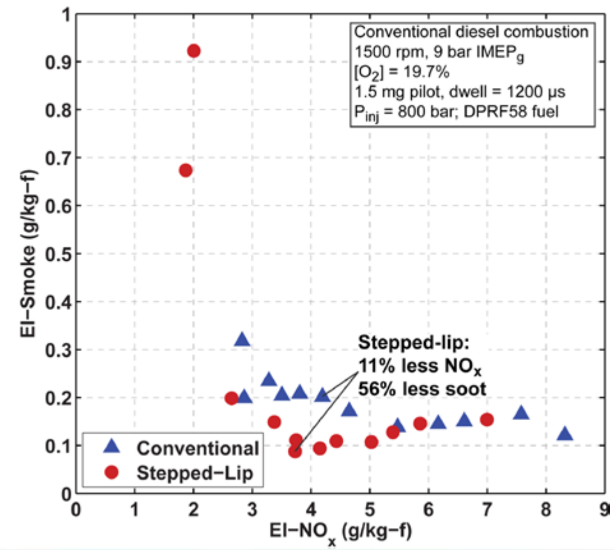
- **Close-coupled pilot injections can reduce soot emissions in light duty, swirl-supported diesel engines, but more research is needed to understand the impact of pilot injections on late-cycle mixing and soot oxidation processes**
- Heavy-duty diesel research (ACE001): close-coupled post injections; late-cycle mixing and soot formation/oxidation in a heavy duty low-swirl engine
- Light-duty diesel research: close-coupled pilot injections in a light-duty, swirl-supported diesel engine
  - Combustion noise reduction via destructive interference[9] (FY15)
  - Close-coupled pilots can reduce engine-out soot emissions[10, 11], but understanding of the soot reduction mechanism is lacking
  - Literature suggests that pilot injections can either support or impede late-cycle mixing and soot oxidation[12]; current understanding is inadequate to provide guidance for injection strategy design
- Sustained experimental (SNL) and computational (UW) research efforts
  - Provide insights into the impact of pilot injections on ignition, combustion, and soot formation/oxidation processes; improve modeling capabilities
  - Support long-term development of conceptual models for multiple injection strategies in both LD and HD engines

TA: simultaneous reductions in fuel consumption and emissions are realized with a stepped-lip piston

- **Conventional diesel combustion**; conventional and stepped-lip pistons have been compared in terms of efficiency, emissions, and combustion phasing
  - With this **stepped-lip piston**, up to a **3% improvement in thermal efficiency** can be achieved for main injection timings after TDC
  - The efficiency improvement is due in part to enhanced rates of late-cycle mixing-controlled combustion; this is in agreement with the literature[6]
  - Gains in efficiency can be realized with **simultaneous reductions in soot and NO_x**
  - Continuing work: analyzing heat transfer effects; investigating mixture formation differences and late-cycle mixing behavior (experiments and numerical simulation)

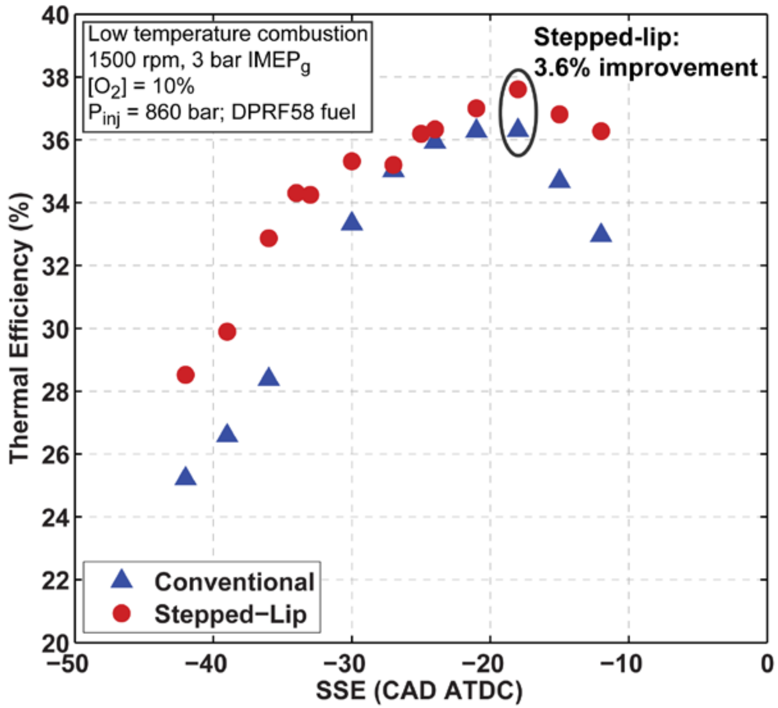


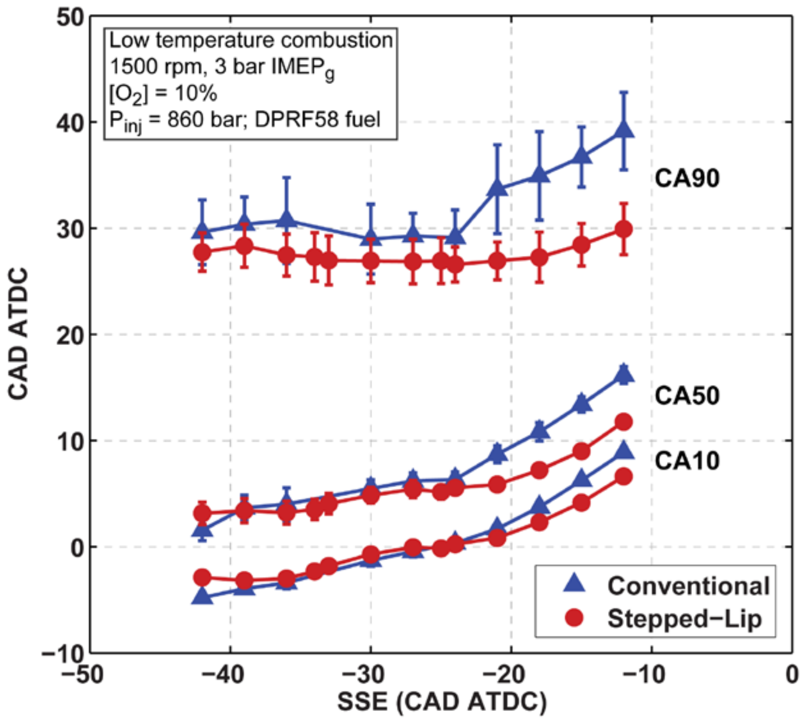




TA: stepped-lip piston bowls can lead to mixing and efficiency benefits for low-temperature combustion

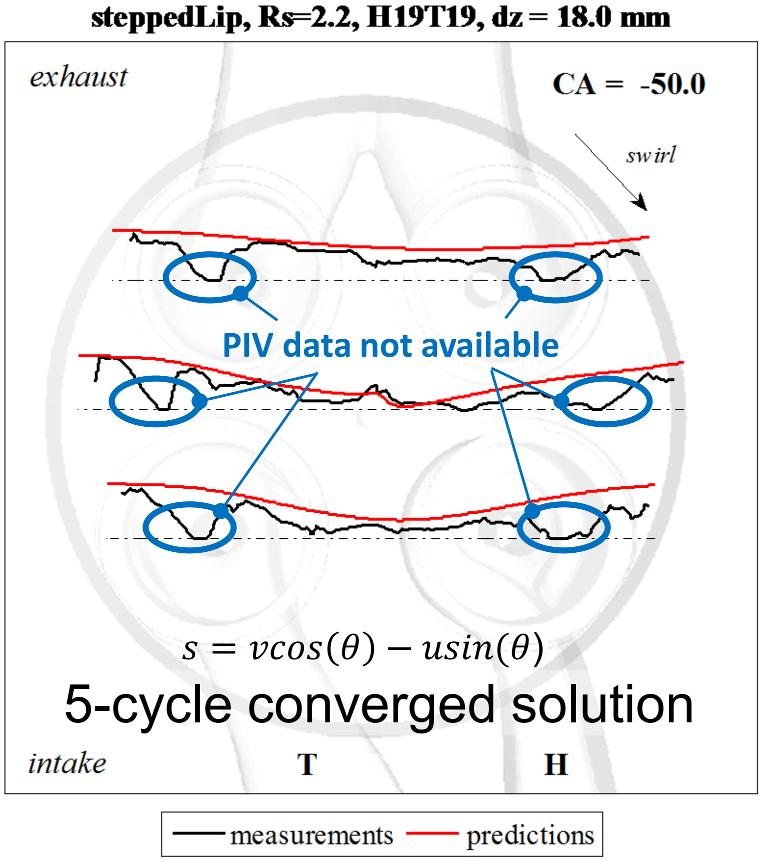
- **Peak thermal efficiency** can be **improved by as much as 3.6%** with a **stepped-lip piston** in a **low-temperature combustion regime**
- For retarded injection cases, **higher heat release rates** are observed with the stepped-lip bowl and are associated with improved mixing (esp. **late-cycle mixing**)
- Continuing work: understanding the effects of injection timing on heat transfer and late-cycle mixing (experiments and numerical simulation)





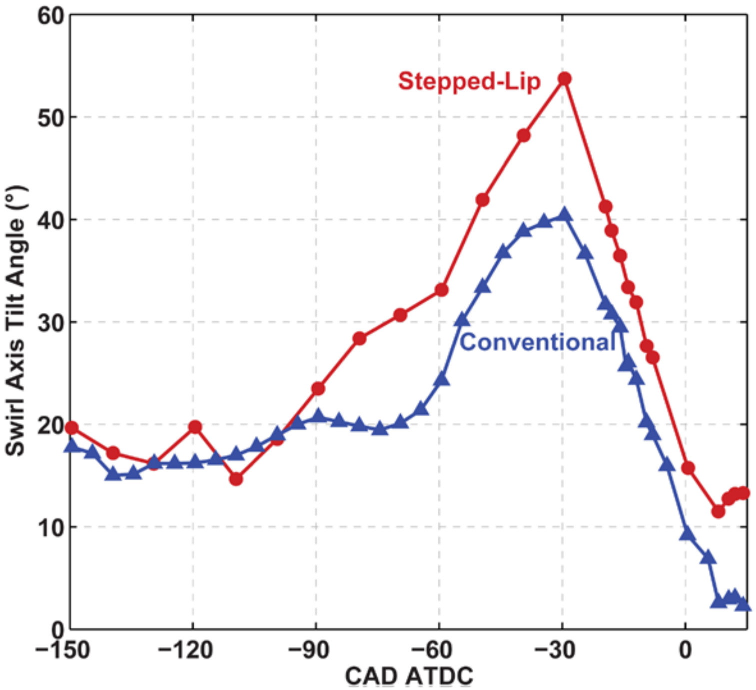
TA: flow topology and swirl magnitudes are well-predicted with UW's multi-cycle CFD simulations

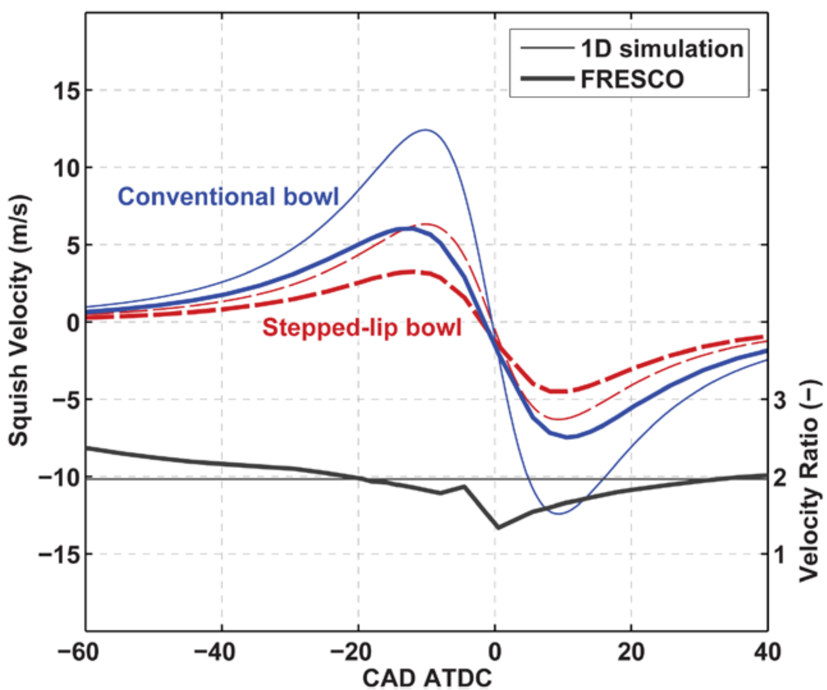
- SNL: swirl-plane PIV measurements have been performed in the optical engine with the stepped-lip piston bowl; the results are used to evaluate UW's RANS simulations
- UW's new CFD code enables simulation of multiple consecutive cycles with a full engine mesh in a matter of days
- Shown: signed tangential velocity along three lines located 18 mm below the fire deck
  - The converged CFD solution agrees well with experimental data where velocity data are available
- **Flow topology is well modeled by UW's converged RANS simulations; this is in agreement with best practices identified in the SNL-CSI-GM collaboration**



TA: simulations demonstrate higher flow asymmetry and weaker squish flow with the stepped-lip bowl

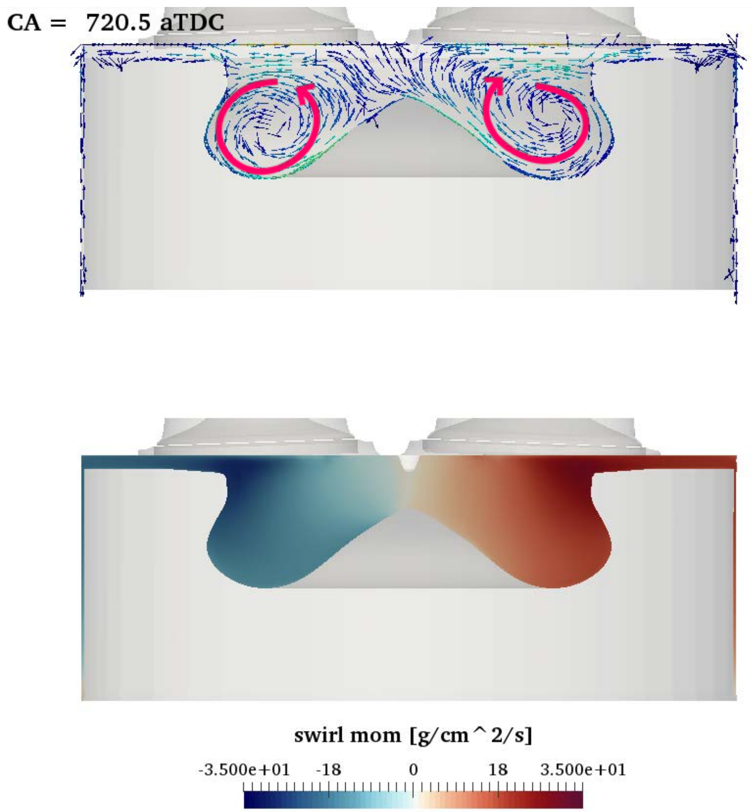
- **Swirl axis tilt (RANS 3D-CFD; PCA)**
  - Swirl axis tilt is higher in the stepped-lip combustion chamber during the second half of the compression stroke
  - The timing of maximum axis tilt is unaffected by bowl geometry
- **Squish velocity (1D model and 3D-CFD)**
  - CFD simulations show reasonable agreement with simplified 1D results
  - Stepped lip bowl compared to conventional bowl: squish velocities ~1/2 as large, squish flow rates ~2/3 as large



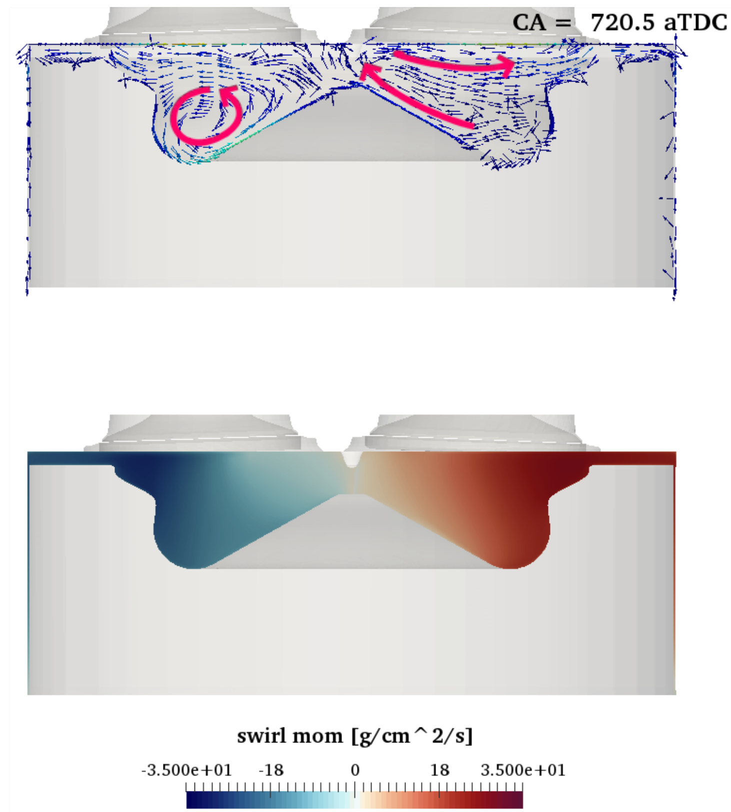


TA: CFD simulations reveal how stepped-lip bowl geometry impacts squish-swirl interactions

- **Conventional bowl**
  - Highly symmetrical vertical-plane flow structures appear as expected
  - Near-TDC: angular momentum concentrated near bowl rim

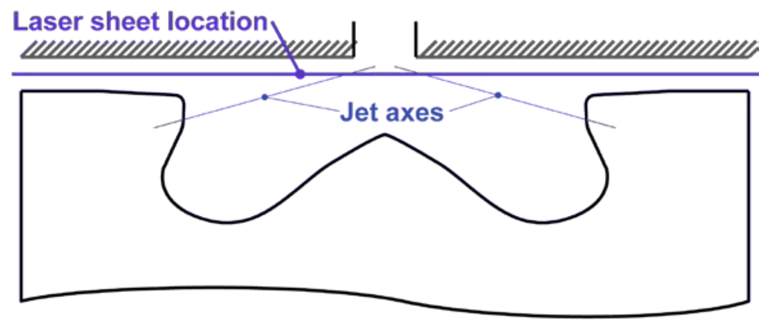


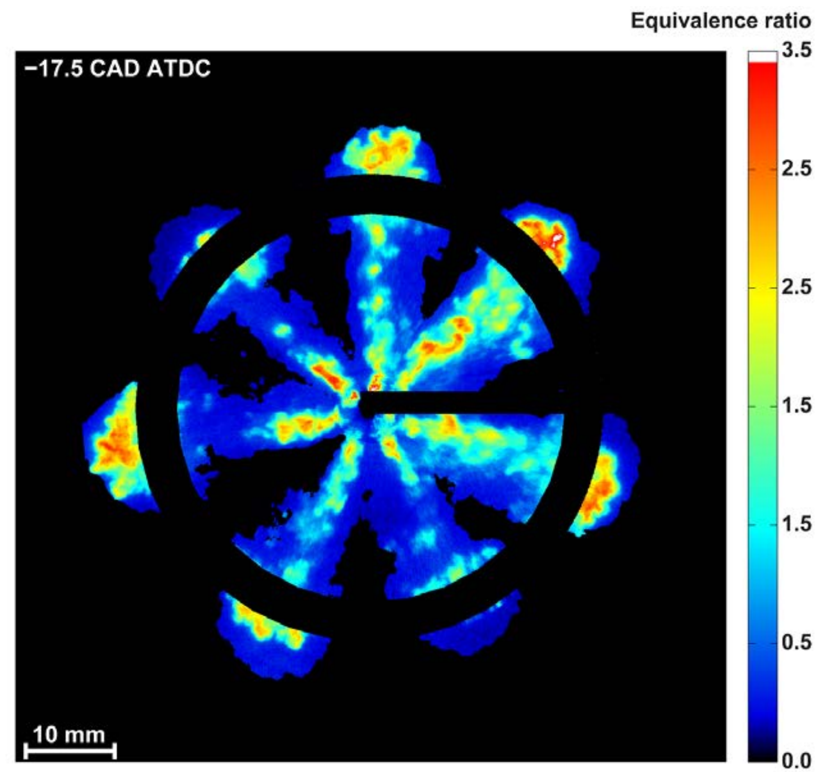
- **Stepped-lip bowl**
  - Greater swirl axis tilt, weaker squish flow: asymmetric vertical-plane flow
  - Angular momentum is distributed over a larger region farther from the center axis



TA: New, quantitative mixture preparation data have been made available to CSI and UW

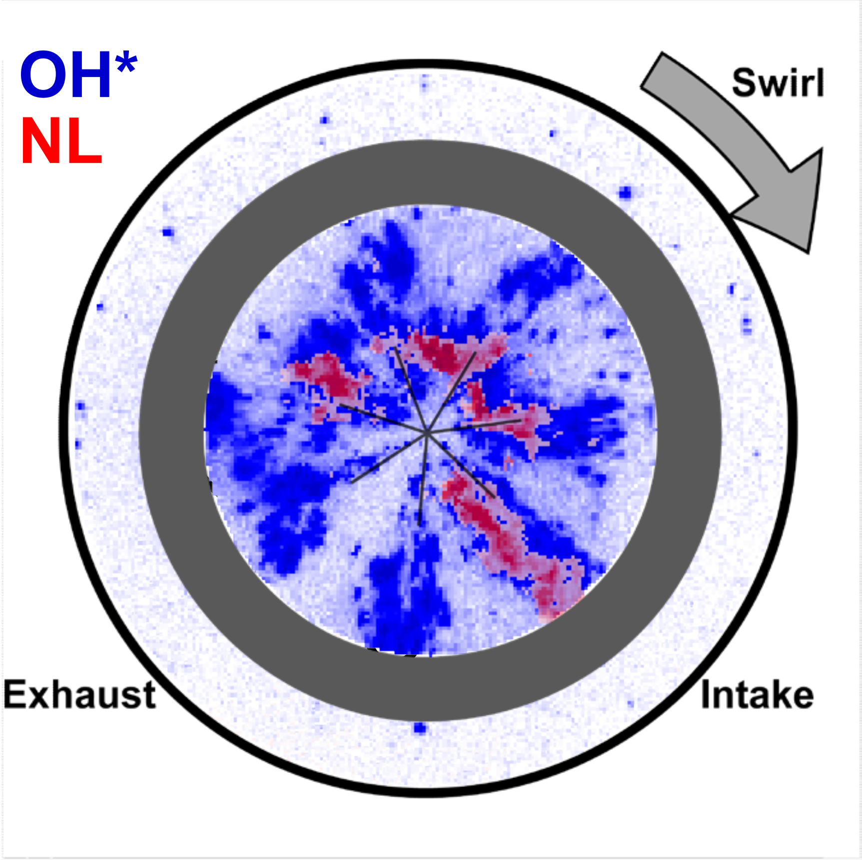
- Refocused collaborative efforts between SNL, CSI, UW, and GM
  - SNL: provide improved, cycle-resolved, quantitative mixture preparation data to CSI and UW
  - CSI: utilize SNL data to evaluate simulation capabilities
  - UW: use SNL data to compare FRESCO simulations with commercial code results and SNL data
  - GM: interact with all parties; provide technical input
  - Combined effort: develop more meaningful methods to compare simulation data with measurements





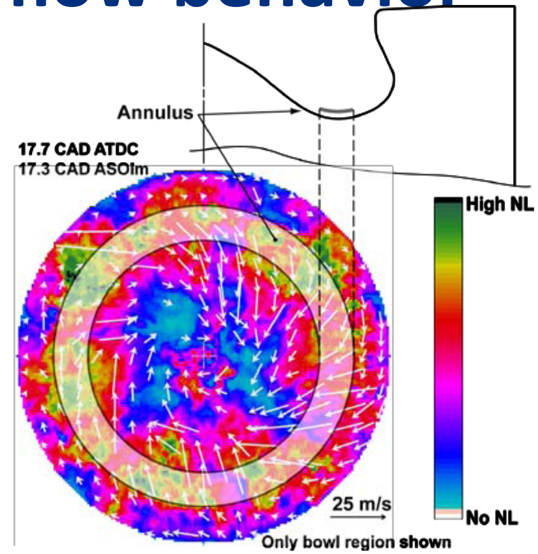
TA: high speed imaging provides insight into main ignition processes with a pilot injection

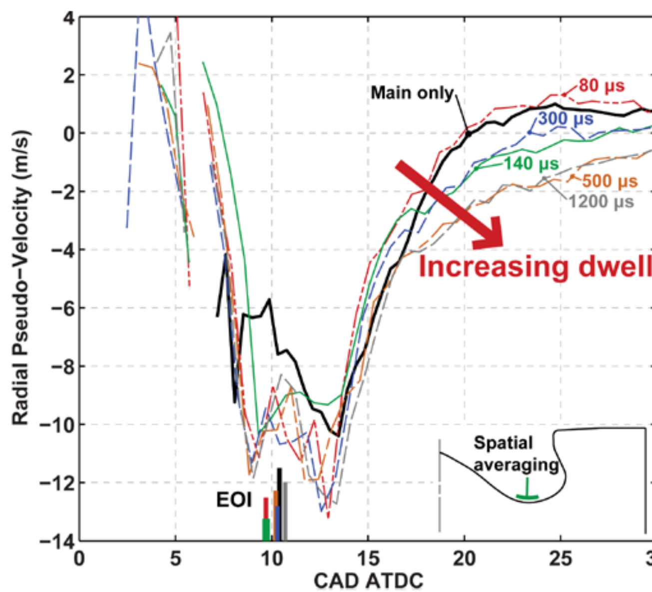
- Simultaneous high-speed OH* chemiluminescence and natural luminosity imaging provides insight into high-temperature main mixture ignition processes with a pilot
- **Three different mechanisms** of **high-temperature ignition** for a given main injection jet are identified:
  - Distributed auto-ignition throughout the jet
  - Localized influence of the jet's still-reactive pilot mixture
  - Localized influence of the neighboring jet's reactive pilot mixture
- Multiple mechanisms may act to ignite a given jet; the process varies from jet-to-jet and cycle-to-cycle
- Continued experimental investigations will support the development of predictive ignition models



TA: a velocimetry technique has been developed to characterize late-cycle bulk flow behavior

- A velocimetry technique has been developed to provide temporally and spatially resolved measurements of flow in the piston bowl during combustion
- Flow in the bowl is characterized for a pilot-main dwell sweep with conventional diesel combustion
  - Literature suggests that engine-out soot decreases with decreasing dwell[11, 12], and that late-cycle oxidation may be influenced by the "design" of pilot injections[13]
- **Increasing pilot-main dwell delays the late-cycle radial flow breakdown in the piston bowl**
  - This radial flow is attributed to vertical-plane vortex structures in the piston bowl, which promote transport and turbulent mixing
- UW is currently preparing CFD simulations to investigate the impact of close-coupled pilots on late-cycle mixing and soot oxidation





Responses to reviewers' comments

- Understanding combustion noise reduction through close-coupled pilots is interesting and much needed, but may not be robust or useful for a production engine. The noise study does not utilize the capabilities of SNL's optical engine, so it should be continued elsewhere, such as at ORNL.

  Response: The analysis was done while the SNL optical engine was being used for another study. Now that the theory of the noise reduction mechanism has been published, the study will hopefully continue as a cooperation with Scott Curran at ORNL (ACE016), although ORNL has neither a diesel project nor expertise in this area. I have worked with Delphi to obtain six state-of-the-art solenoid injectors that will enable study of close-coupled pilots.

- There needs to be much stronger coordination with the engine manufacturers and with ORNL.

  Response: We coordinate closely with diesel R&D groups at GM and Ford. Frequent meetings and teleconferences are held to discuss results, planned studies, and the development of UW's CFD code. The collaboration with ORNL is being developed and should grow stronger in the coming year as technical preconditions are addressed.

- Research efforts need to be directed towards thermomechanical material stress issues.

  Response: This has been discussed with industry partners and with the DOE program manager and deemed to be outside the scope of this project. The AHEAD consortium at SwRI appears to be focused on this important topic.

- It is unclear where the GM 1.9L engine is used.

  Response: The SNL optical engine is built with a GM 1.9L cylinder head, and the conventional piston bowl resembles the production-intent geometry. Simulation efforts at both CSI and UW are performed with this configuration, although the computational meshes used by these groups are different.

- Squish flow behavior should be understood early by exercising the CFD model.

  Response: Agreed. UW's CFD simulation platform is being used for this purpose.

- UW and SNL are apparently now using Converge in this project.

  Response: There appears to be some confusion about this. UW does not use Converge to support the light-duty research. They have developed their own parallel, open-source CFD platform called Fast and Reliable Engine Simulation Code (FRESCO). Please see backup slides for details about FRESCO and why it has been developed.

Future work

- **Experiments**
  - Pilot injections: CH_2O-PLIF imaging; providing support for emerging theory of low-temperature chemistry – turbulence interactions; these insights may lead to simpler, more accurate ignition models
  - Bowl geometry: comparison of mixture formation processes via quantitative fuel-tracer PLIF measurements; development of infrared fuel vapor imaging technique to complement quantitative PLIF data
  - Collaboration with ORNL: close-coupled pilot injections; effects on efficiency, noise, and soot emissions in a near-production engine
- **Analysis**
  - Expand analytical capabilities to estimate/quantify wall heat losses; apply to bowl geometry study to better understand efficiency
  - (with UW): CFD study of spray-swirl interactions and how they are impacted by piston bowl geometry; impact of piston bowl geometry on late-cycle mixing and heat release
  - (with UW): CFD study: impact of pilot injection on late-cycle mixing and soot oxidation; comparison with experimental results

Summary

- **Relevance**
  - Research is necessary to improve the efficiency and emissions of light-duty diesel engines
  - Stepped-lip piston bowls improve efficiency, but fundamental understanding is lacking
  - Close-coupled pilot injections may be used to reduce soot emissions; the mechanism is not understood
- **Approach**
  - Close collaboration with industry partners to define project direction; subcontract with UW to provide supplemental insights using 3D-CFD simulations; active collaboration to support commercial code development (CSI); developing collaborative efforts with ORNL and ANL
- **Technical Accomplishments**
  - Simultaneous improvements in efficiency and emissions are realized with the SNL stepped-lip piston; future studies will provide insight into the underlying mechanisms
  - Preliminary CFD results demonstrate significant differences between the conventional and stepped-lip pistons in terms of in-cylinder flow asymmetry, squish flow, and consequently squish-swirl interactions
  - Imaging data has provided insight into high-temperature main ignition processes with a pilot injection
  - Experimental velocimetry data indicates that pilot-main dwell impacts late-cycle radial flow breakdown
- **Collaborations**
  - Close collaboration with GM, Ford R&D groups; interaction with other industry partners at AEC meetings
  - Subcontract with UW – new CFD code will continue to provide insight beyond experimental observations
  - Collaboration with CSI – using state-of-the-art experimental data to evaluate and improve commercial code
  - Developing collaborations with ORNL / ANL – utilizing each facility's strengths, enabling future cooperation
- **Future Work**
  - Focus on late-cycle mixing: close-coupled pilot injections and piston bowl geometry

Technical Back-Up Slides

References

1. “2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards”, Final Rule, EPA–HQ–OAR–2010–0799, 77:199 (Oct. 15, 2012).
2. “Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards”, US EPA, Final Rule, EPA-HQ-OAR-2011-0135, 79:81 (Apr. 28, 2014)
3. “Light-Duty Noise Guidelines for Advanced Combustion Research,” 2015, United States Council for Automotive Research, Advanced Powertrain Technical Leadership Council: http://www.uscar.org/guest/tlc/1/Advanced-Powertrain.
4. Styron, J., Baldwin, B., Fulton, B., Ives, D. and Ramanathan, S., "Ford 2011 6.7L Power Stroke® Diesel Engine Combustion System Development," SAE Technical Paper 2011-01-0415, 2011, DOI: 10.4271/2011-01-0415
5. Eder, T., Lückert, P., Kemmner, M., Sass, H. , "OM654 – Start einer neuen Motorfamilie bei Mercedes-Benz," MTZ - Motortechnische Zeitschrift 77(3):62-69, 2016.
6. Kurtz, E. M. and Styron, J., "An Assessment of Two Piston Bowl Concepts in a Medium-Duty Diesel Engine," SAE Int. J. Engines 5(2):344-352, 2012, DOI: 10.4271/2012-01-0423.
7. Dolak, J. G., Shi, Y. and Reitz, R. D., "A Computational Investigation of Stepped-Bowl Piston Geometry for a Light Duty Engine Operating at Low Load," SAE Technical Paper 2010-01-1263, 2010, DOI: 10.4271/2010-01-1263.
8. Fridriksson, H. S., Tuner, M., Andersson, O., Sunden, B., Persson, H. and Ljungqvist, M., "Effect of Piston Bowl Shape and Swirl Ratio on Engine Heat Transfer in a Light-Duty Diesel Engine," SAE Technical Paper 2014-01-1141, 2014, DOI: 10.4271/2014-01-1141.
9. Busch, S., Zha, K., Warey, A., Pesce, F. C. and Peterson, R., "On the Reduction of Combustion Noise by a Close-Coupled Pilot Injection in a Small-Bore Direct Injection Diesel Engine," Journal of Engineering for Gas Turbines and Power 2016, DOI: 10.1115/1.4032864
10. Badami, M. M., F.; Millo, F.; Rossi, E.E., "Experimental Investigation on the Effect of Multiple Injection Strategies on Emissions, Noise and Brake Specific Fuel Consumption of an Automotive Direct Injection Common-Rail Diesel Engine," Int. J. Engine Res. 4(4):299-314, 2003, DOI: 10.1243/146808703322743903.
11. Kastner, O., Atyler, F., Müller, A, Weigand, A., Wenzlawski, K., Zellbeck, H., "Multiple Injection Strategies and their effect on pollutant emission in passenger car diesel engines," presented at THEISEL 2006, Valencia, Spain.
12. Miles, P. C., "Turbulent Flow Structure in Direct-Injection, Swirl-Supported Diesel Engines", in Flow and Combustion in Reciprocating Engines, 2008, 10.1007/978-3-540-68901-0_4.

List of Publications

Conference Papers

Perini, F., Zha, K., Busch, S., Miles, P. and Reitz, R. D., "Principal Component Analysis and Study of Port-Induced Swirl Structures in a Light-Duty Optical Diesel Engine," SAE Technical Paper 2015-01-1696, 2015, DOI: 10.4271/2015-01-1696.

Journal Papers

Busch, S., Zha, K., Warey, A., Pesce, F. C. and Peterson, R., "On the Reduction of Combustion Noise by a Close-Coupled Pilot Injection in a Small-Bore Direct Injection Diesel Engine," Journal of Engineering for Gas Turbines and Power 2016, DOI: 10.1115/1.4032864.

Zha, K., Busch, S., Miles, P. C., Wijeyakulasuriya, S., Mitra, S. and Senecal, P. K., "Characterization of Flow Asymmetry During the Compression Stroke Using Swirl-Plane PIV in a Light-Duty Optical Diesel Engine with the Re-entrant Piston Bowl Geometry," SAE Int. J. Engines 8(4):1837-1855, 2015, DOI: 10.4271/2015-01-1699.

Fuel efficiency improvement is observed with stepped-lip piston geometry under single-injection, EGR-diluted LTC conditions.

- The stepped-lip piston has fuel efficiency advantages both at early-injection and retarded injection timings.
- With early-injection timings, lower CO emissions are observed with the stepped-lip piston; combustion efficiency is degraded
- UHC emissions are similar for both piston geometries.