

# Light- and Medium-Duty Diesel Combustion

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June 19, 2018

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**Project ID: ACS002**

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# Overview

## Timeline

- 2004-2017: light-duty diesel research; flow, turbulence, mixture preparation, combustion, pollutant formation, and low temperature combustion
- May 2017: LD-diesel research slated for elimination in FY18 congressional budget justification
- December 2017: direction from DOE to shift project focus to medium-duty diesel combustion

## Budget

- FY17: \$885k
- FY18: \$200k
  - Subcontract with UW/WERC: \$107k

## Barriers/Technical targets (USDRIVE / ACEC roadmap)

- Lack of quantitative databases on an engine combustion system precludes collaborative model verification and validation
- Inadequate understanding of fundamentals of fuel injection, air motion, and combustion chamber geometry on combustion and pollutant formation
- Research priorities for clean diesel combustion
  - Reduced engine-out NOx and particulates
  - Reduced cold-start emissions

## Partners

- W-ERC (Prof. Reitz, Dr. Federico Perini)
  - Subcontractor
- UW-Madison (Prof. Kokjohn)
- Ford
- General Motors
- Cummins



# Relevance/objectives: piston bowl geometry study

## • Current state-of-the-art

- Available literature provides partial descriptions of spray-wall interactions and flow evolution with stepped-lip pistons and often associates them with benefits in efficiency and emissions [1-7], but a science-based understanding of the mechanisms responsible for the formation of beneficial flow structures is lacking.

## • Overall Objectives:

- Create a conceptual model from detailed scientific understanding of swirl-supported diesel combustion including spray-swirl and spray-wall interactions
- Provide science-driven guidance for combustion system design

## • Objectives this period:

- Process combustion image velocimetry data to characterize the evolution of turbulent flow structure in both the conventional and stepped-lip pistons and its sensitivity to injection timing
- Develop fundamental, scientific understanding of mechanisms that create beneficial flow structures associated with efficiency and emissions improvements with the stepped-lip combustion chamber, and of the sensitivity of these mechanisms to injection timing

## • Impact:

- A quantitative database of engine geometry data, experimental results, and documentation on the ECN website enables collaboration with CFD modeling and simulation groups
- A science-based understanding of how jet-wall interactions and engine design/calibration parameters impact turbulent flow evolution, mixing behavior, combustion, and pollutant formation will provide knowledge and insight necessary for industry to develop the next generation of clean diesel engines.

[1] Smith, A., "Ricardo low emissions combustion technology helps JCB create the off-highway industry's cleanest engine," [Press Release]. R. M. Office, March 18, 2010. Retrieved from <https://ricardo.com/news-and-media/press-releases/ricardo-low-emissions-combustion-technology-helps>.

[2] Eder, T., Lückert, P., Kemmner, M., Sass, H., "OM654 – Launch of a New Engine Family by Mercedes-Benz," MTZ Worldwide, 77(3):60-67, 2016

[3] Dakhore, R., Gandhi, N. G., Gokhale, N., Aghav, Y., Kumar, M. N. and Hulwan, D. B., "Effect of Piston Cavity Geometry on Combustion, Emission and Performance of a Medium Duty DI Diesel Engine," SAE Technical Paper 2015-26-0198, 2015, DOI: <https://doi.org/10.4271/2015-26-0198>

[4] Iikubo, S., Nakajima, H., Adachi, Y. and Shimokawa, K., "Combustion chamber structure for direct injection diesel engine", Patent Number: US 8,156,927 B2, April 17, 2012

[5] 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

[6] Lee, J., Lee, S., Kim, J. and Kim, D., "Bowl Shape Design Optimization for Engine-Out PM Reduction in Heavy Duty Diesel Engine," SAE Technical Paper 2015-01-0789, 2015, DOI: <https://doi.org/10.4271/2015-01-0789>

[7] Leach, F., Ismail, R., Davy, M., Weall, A. and Cooper, B., "Comparing the Effect of Fuel/Air Interactions in a Modern High-Speed Light-Duty Diesel Engine," SAE Technical Paper 2017-24-0075, 2017, DOI: <https://doi.org/10.4271/2017-24-0075>



# Relevance/objectives: catalyst heating operation study

## • Current state-of-the-art

- Untreated cold-start emissions remain as a barrier to meeting future emissions regulations [1,2]. Post-injection strategies are used to increase exhaust enthalpy to heat up catalysts [3], but result in tradeoffs in fuel consumption, exhaust enthalpy, and HC / CH<sub>2</sub>O / NO<sub>x</sub> / PM emissions [4,5]. Current scientific understanding is insufficient to provide science-based guidance on catalyst heating operation.

## • Overall objectives

- Achieve stable ignition/combustion of post injections; maximize exhaust temperature/enthalpy with minimal untreated emissions for catalyst heating operation
- Develop conceptual models of mechanisms responsible for tradeoffs between combustion system design/operation parameters and exhaust enthalpy/emissions/fuel consumption

## • Objectives this period

- Establish working group
  - Technical advising from industry partners
  - Capability to rapidly screen multiple injection strategies and identify tradeoffs in exhaust enthalpy and pollutant emissions
- Begin developing new experimental/optical diagnostic capabilities to detect CH<sub>2</sub>O in the exhaust and in-cylinder
- Identify relevant operating conditions to explore tradeoffs between efficiency, exhaust enthalpy, and criteria pollutant emissions with the GM 1.9L combustion system

## • Impact

- Catalyst heating strategies based on scientific understanding of tradeoffs between operating parameters and exhaust enthalpy/emissions will minimize catalyst heating time, untreated pollutant emissions, and fuel consumption
- Optical measurements will provide datasets for collaborative evaluation/development of CFD models

[1] Neely, G. D., Sarlashkar, J. V. and Mehta, D., "Diesel Cold-Start Emission Control Research for 2015-2025 LEV III Emissions," SAE International Journal of Engines 6(2):1009-1020, 2013, DOI: <https://doi.org/10.4271/2013-01-1301>

[2] CARB, 2012. "Final Regulation Order, LEV III Amendments", California Code of Regulations, Title 13, Sections 1900, 1956.8, 1960.1, 1961, 1961.2, 1961.3, 1962.1, 1962.2, and 1976, As amended: December 6, 2012  
<http://www.arb.ca.gov/regact/2012/leviiidtc12/leviiifrorev.pdf>

[3] Mercuri, D., Pozzi, C., Nati, G., Cassani, S., "Multi-After Injection Strategy to Optimize Exhaust Gases Temperature and Combustion Stability in Diesel Engine," presented at 24th Aachen Colloquium Automobile and Engine Technology, Aachen, Germany, October 5-7, 2015

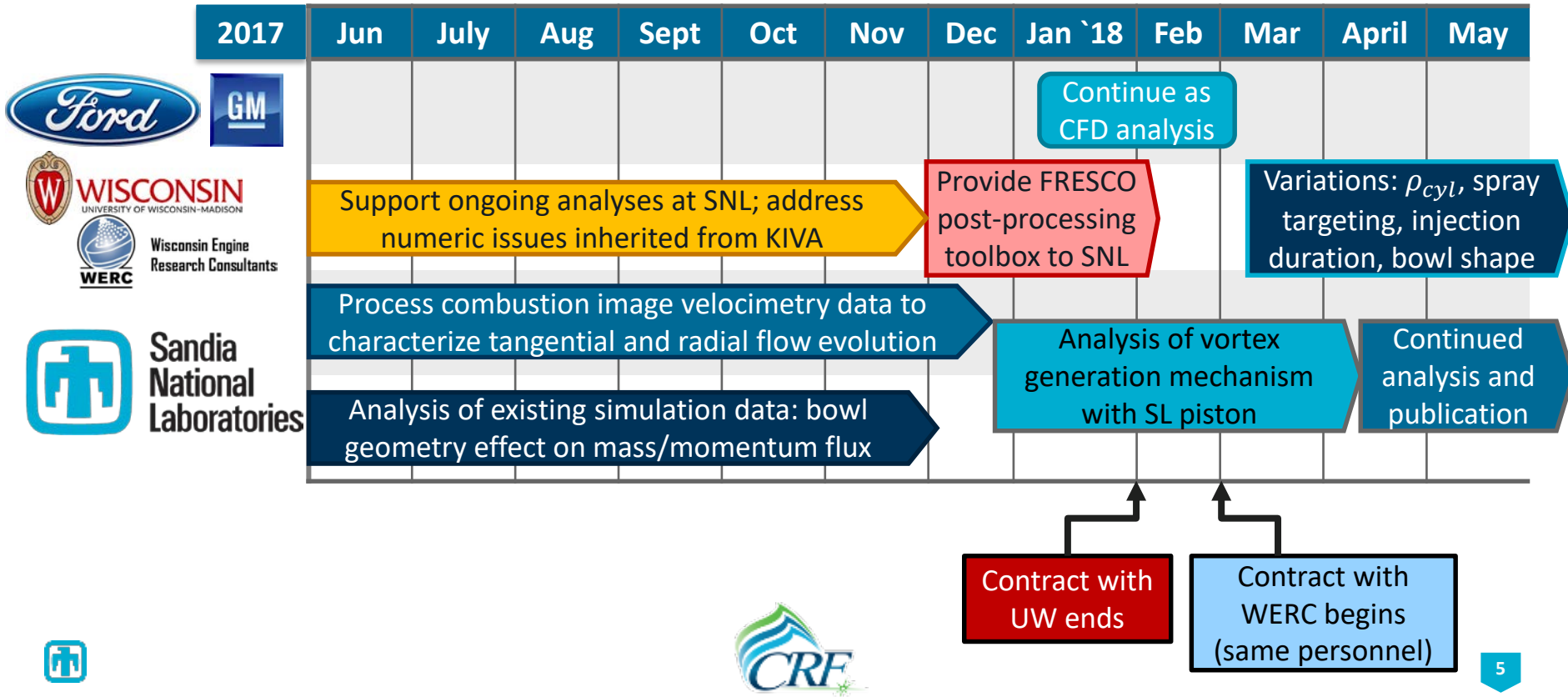
[4] Kurtz, E. and Polonowski, C. J., "The Influence of Fuel Cetane Number on Catalyst Light-Off Operation in a Modern Diesel Engine," SAE International Journal of Fuels and Lubricants 10(3):2017

[5] Personal communication with Eric Kurtz, Ford Motor Company



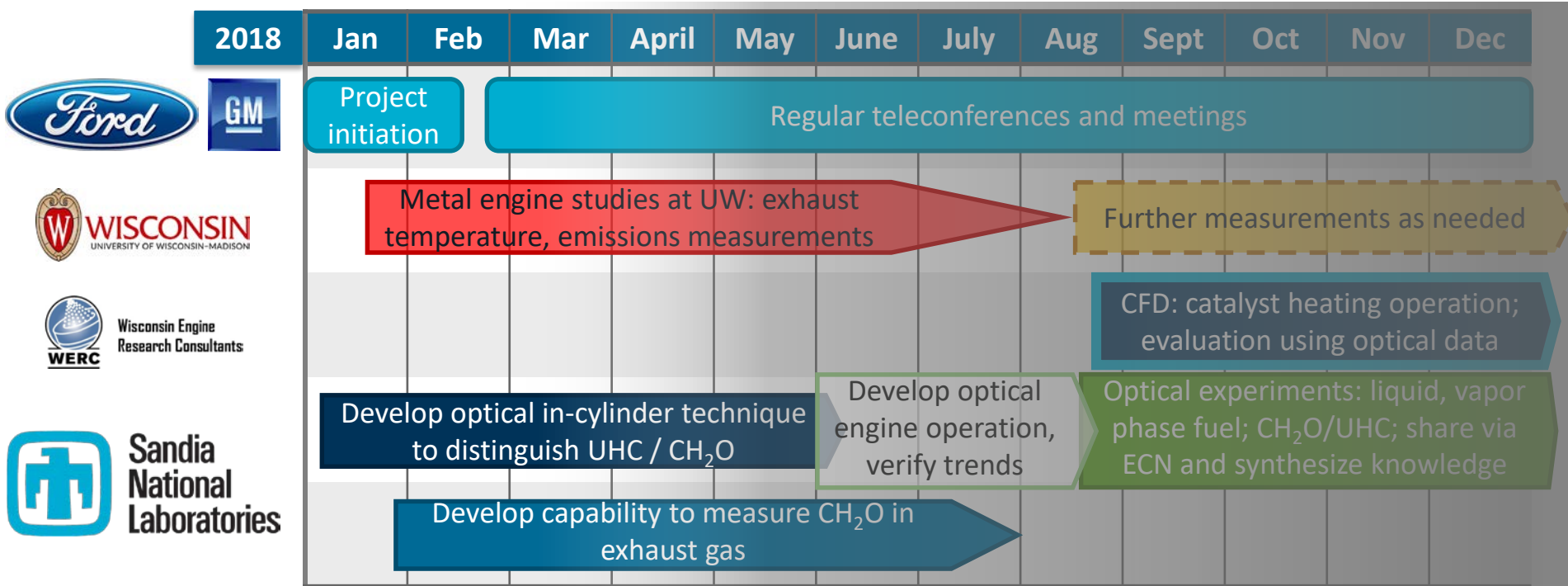
## Approach/strategy: piston bowl geometry study

- Analysis of experimental combustion image velocimetry data has concluded
- Decision made with input from Ford, GM: continue this study with CFD
  - Parametric variations to understand impacts of changing operating parameters
- FRESKO post-processing toolbox has helped create a framework to understand ongoing parametric studies and shape future bowl shape sensitivity studies



## Approach/strategy: catalyst heating study

- Technical guidance from Ford and GM through regular meetings
- Operating strategy development at UW-Madison using all-metal GM 1.9L engine
- Optical studies performed on SNL's engine (based on GM 1.9L combustion system)



\*No further light-duty diesel research will be conducted at SNL

## TA: quantitative database established via ECN website

<https://ecn.sandia.gov/engines/engine-facilities/small-bore-diesel-engine/>

- Geometric data to enable collaborative CFD simulation efforts:
  - Full engine geometry surface model, including conventional and stepped-lip pistons
  - Crank-slider relationship data
  - Valve lift and flow coefficient data
  - Spray targeting information
- Quantitative experimental data include:
  - Boundary conditions (pressures, temperatures, injection rate profiles)
  - Cylinder pressure / heat release data
  - PIV: distortion-corrected velocity fields
  - High-speed liquid fuel imaging: time-resolved liquid length and spreading angle
  - Fuel-tracer PLIF: quantitative fuel concentration from three swirl-planes
  - Combustion image velocimetry: flow information during mixing-controlled combustion
- Collaborative efforts:
  - Cummins: active collaboration to evaluate combustor flow predictions using CONVERGE
  - CD-Adapco: interested, but waiting on re-formatted engine geometry files
  - CSI: has been working with to build meshes with the available geometry

**Building this quantitative database directly supports a technical strategy defined by the ACEC tech team to address major barriers to advanced diesel combustion system technology**



## TA: initial calibration of CFD simulations completed at Cummins using SNL's ECN database

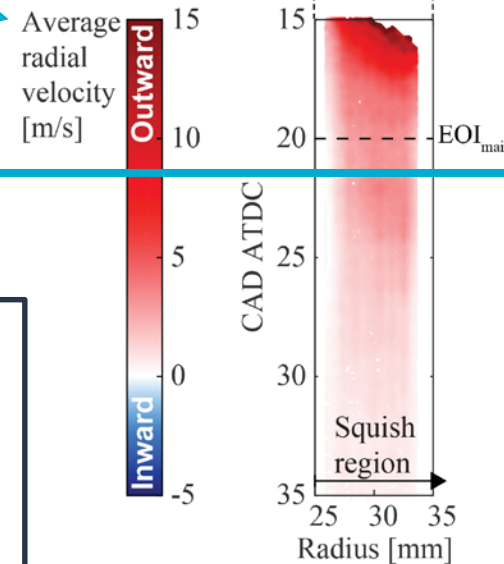
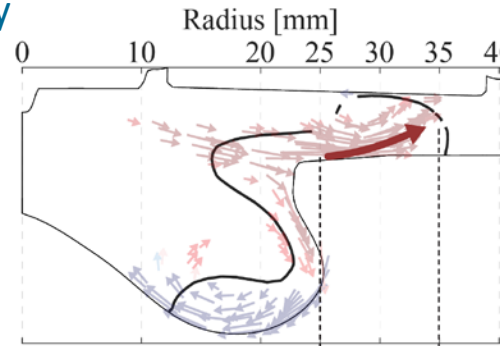
- Cummins has created computational meshes of the 1.9L engine with both the conventional and stepped-lip pistons for CONVERGE simulations
  - Purpose is to evaluate CFD approaches: RANS vs LES
- Ongoing discussions focus on making meaningful comparisons between experimental data and CFD results
  - There are currently no plans to adapt the FRESKO postprocessing toolbox to enable analysis of CONVERGE results
- Cummins has completed calibration of their combusting simulations using SNL's cylinder pressure and heat release rate traces (available on the ECN database)
  - Simulations with each piston geometry and three injection timings are underway



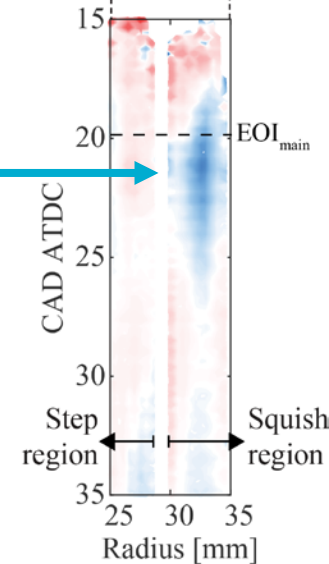
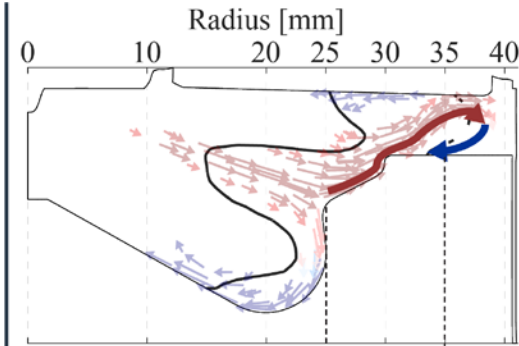


# TA: experimental characterization of flow patterns above the stepped-lip and conventional pistons

## Conventional piston



## Stepped-lip piston



- CIV: cross correlation between pairs of high-speed natural luminosity images yields velocity information (FY16)

- FY17: analysis of CIV results reveals the evolution of radial flow above the conventional and stepped-lip pistons

- False-color images show azimuthal and ensemble averaged radial velocity as a function of radius and crank angle

- Inward flow observed in the squish region is evidence of a vortex that is unique to the stepped-lip piston

- This first experimental characterization of in-cylinder flow during mixing-controlled combustion with both pistons provides:

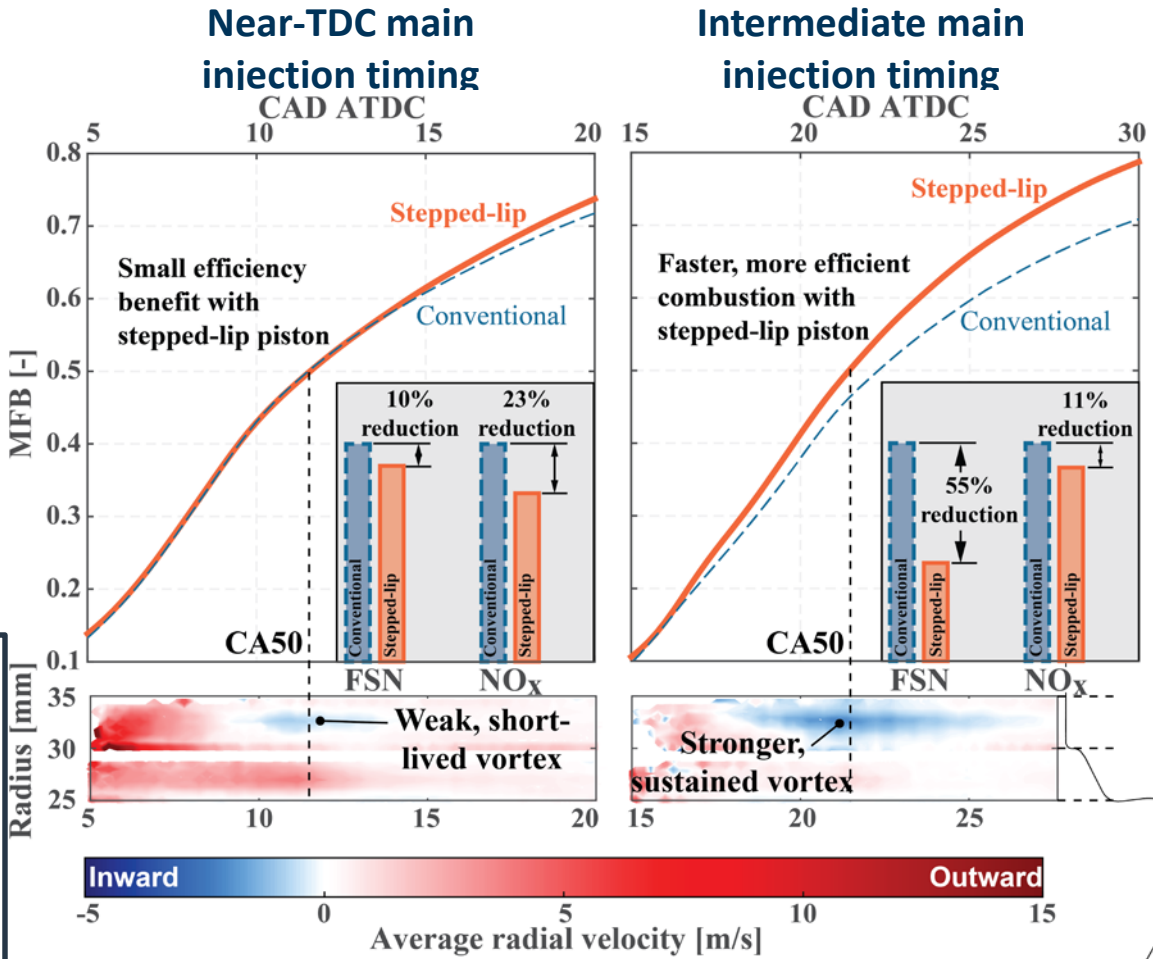
- Improved understanding of how bowl geometry influences flow structure
  - Quantitative dataset for collaborative CFD code validation (available via ECN)



# TA: analysis of experimental data reveals sensitivity of vortex evolution to injection timing

- Experimental evidence shows efficiency and soot emissions advantages of the stepped-lip piston correlate with the intensity/longevity of the squish-region vortex
- This finding supports, but does not prove, a theory proposed in the literature that enhanced air utilization in the squish region enhances mixing with the stepped-lip piston [1]

- Flow structures associated with emissions and efficiency benefits are sensitive to injection timing
  - Further efficiency and emissions improvements may be realized if these vortices can be strengthened at near-TDC injection timings



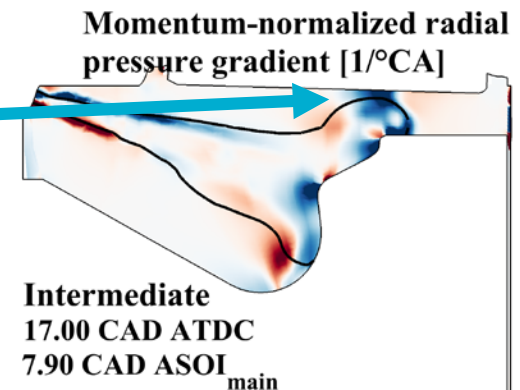
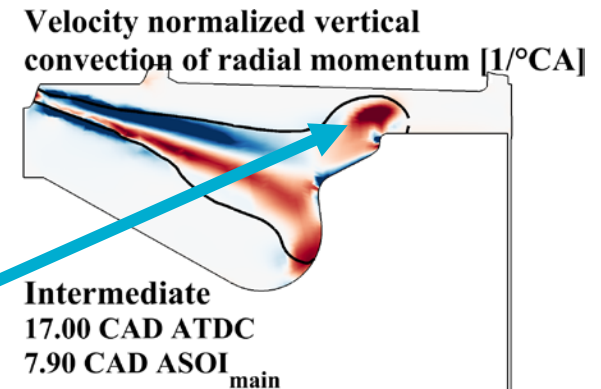
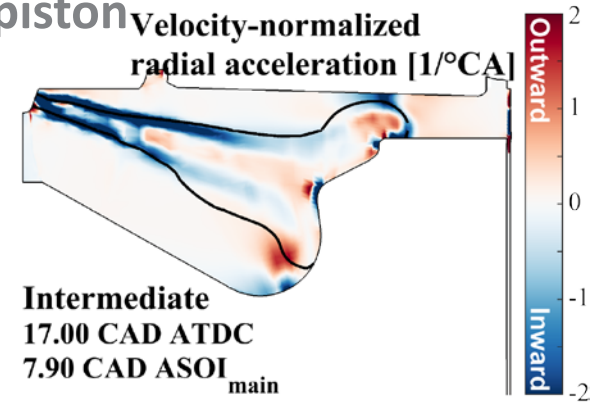
[1] Kurtz, E. M. and Styron, J., "An Assessment of Two Piston Bowl Concepts in a Medium-Duty Diesel Engine," *SAE Int. J. Engines* 5(2):344-352, 2012, DOI: 10.4271/2012-01-0423



# TA: CFD analysis provides explanation of the physics responsible for vortex formation above the stepped-lip piston

- Federico Perini (WERC) provided SNL with a MATLAB toolbox to enable post-processing of FRESKO CFD simulation results
- Cartesian-based CFD results are used to evaluate and visualize the terms of the velocity-normalized RANS radial momentum equation
  - See backup slide for details

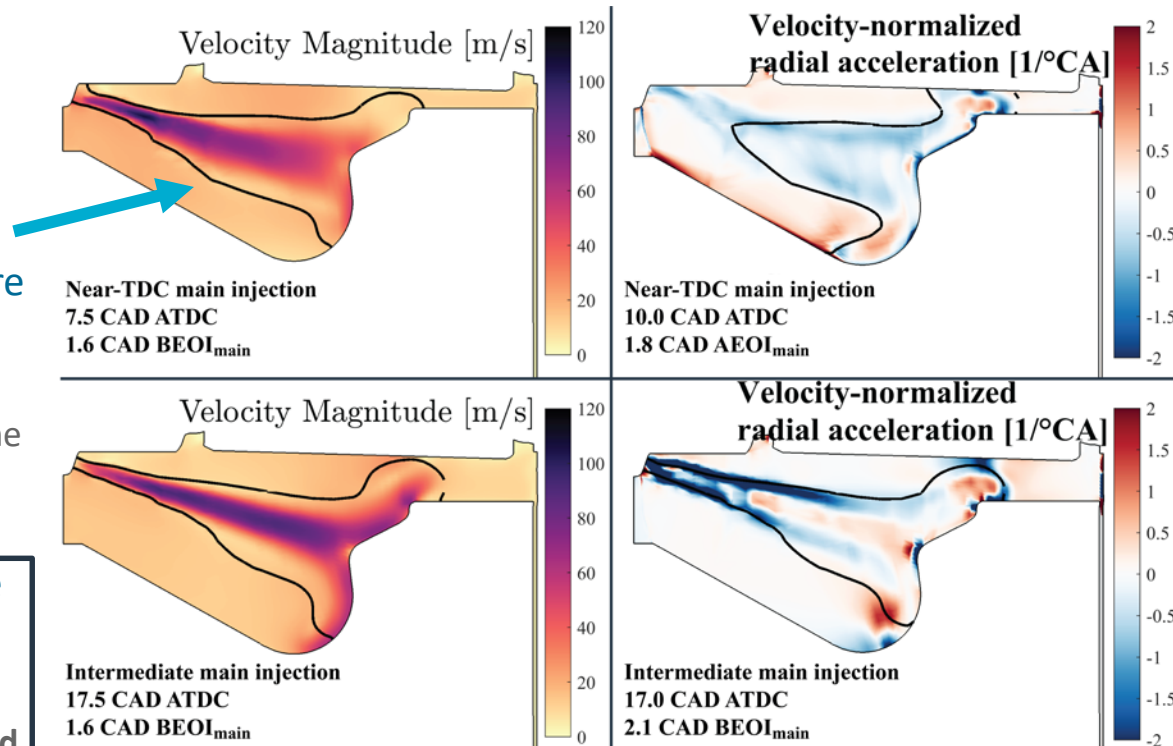
- This analysis provides new understanding of how jet-wall interactions manipulate in-cylinder flow:
  - The step imparts upward momentum to the jets; vertical convection of the jets' radial momentum drives outward, upward flow that forms the vortex in the squish region
  - The high pressure region in front of the jets stagnates in the squish region and the adverse radial pressure gradient drives flow inward along the cylinder head to form the inner, upper vortex



# TA: air entrainment and jet velocity identified as important factors in vortex formation with the stepped-lip piston

- Ambient density changes with injection timing and affects air entrainment, jet structure, and penetration velocity
- For injection timings closer to TDC, the jets entrain more air and penetrate more slowly
  - Near-TDC injection timing: secondary jet separates from the piston surface after the end of injection (AEOI<sub>main</sub>)

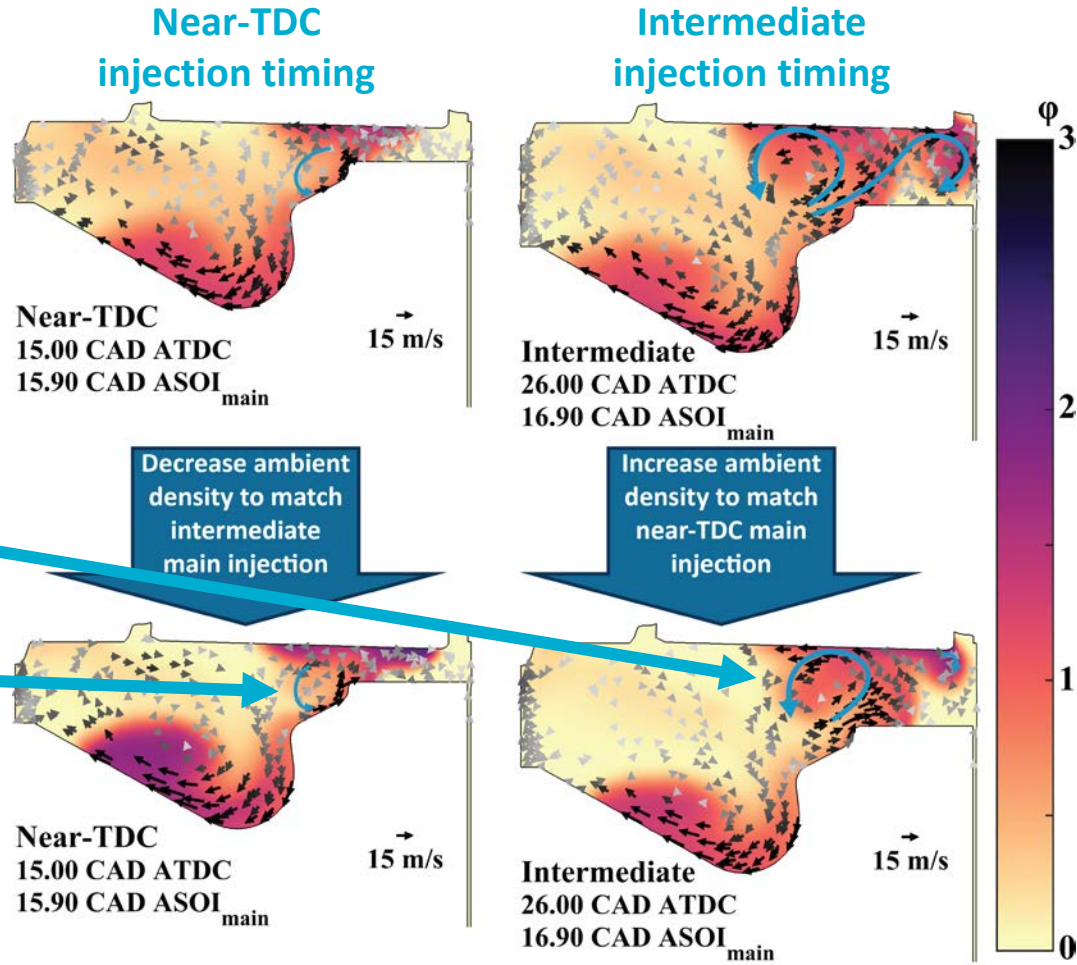
- The factors driving vortex formation are present for both the intermediate and near-TDC injection timings
  - Jet velocity / momentum distribution and the relative timing of jet-wall interactions are an important consideration when calibrating / optimizing a stepped-lip combustion chamber



The FRESKO CFD simulation dynamically adjusts the near-field spreading angle of the jets in response to changing ambient density; higher densities mean more air entrainment, a higher spreading angle, and lower jet velocities. This results in a later, less energetic interaction with the piston bowl surface. Distinguishing spray targeting effects from ambient density effects requires further simulations with varying intake pressure.

# TA: spray targeting and piston-head proximity identified as important factors in vortex formation with the stepped-lip piston

- FRESCO CFD simulations were performed with variations in intake pressure to investigate the effect of ambient density
  - Intermediate injection timing: increase density to match near-TDC injection timing case
  - Near-TDC injection timing: decrease density to match intermediate injection timing case
- Increasing ambient density for the intermediate injection timing impedes vortex formation in the squish region
- Decreasing ambient density for the near-TDC injection timing does not restore the vortices observed with the intermediate injection timing
- Changes in spray targeting and/or piston-head proximity must also play a key role in vortex generation with the stepped-lip piston

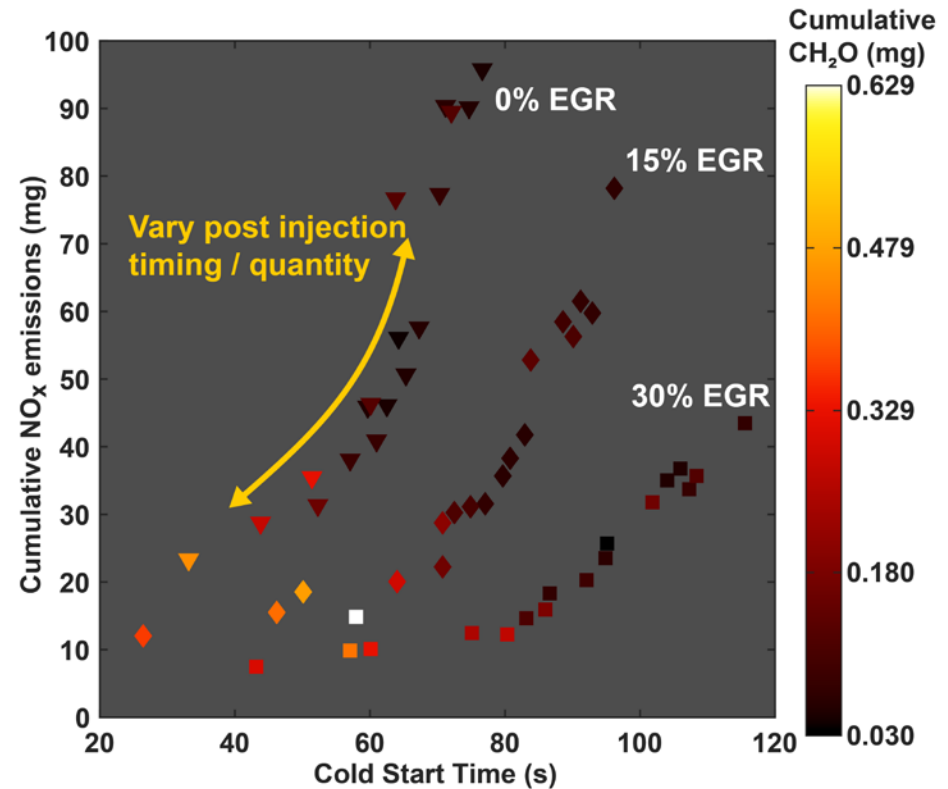
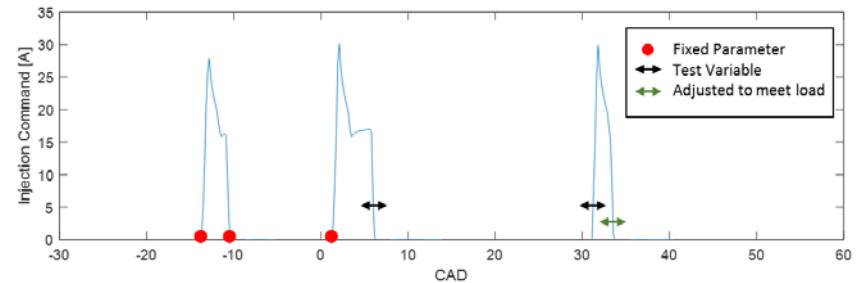




# TA: initial characterization of GM 1.9L engine in catalyst heating operation at UW-Madison

- Preliminary characterization of the GM 1.9L combustion system is complete for a pilot-main-post injection strategy
- The following parameters have been varied:
  - Post injection quantity and timing
  - EGR rate
- Tradeoffs between exhaust emissions and exhaust enthalpy show different sensitivities to operating parameters than a different OEM combustion system
  - Further characterization work will continue at UW-Madison – a larger parameter space will be explored based collaborative discussions with Ford

**Progress is being made to identify relevant operating conditions to explore tradeoffs in catalyst heating operation with optical measurements and CFD simulations**



With the GM 1.9L engine and a pilot-main-post injection strategy, there is an inherent trade-off between  $\text{NO}_x$  (y-axis),  $\text{CH}_2\text{O}$  emissions (color), and cold start time (x-axis)

# Responses to reviewer comments

A parametric CFD study for assessing piston bowl parameters for efficiency, and validation using experimental studies will be vital to the engine community. The bowl geometry study also needs to consider a space of air-fuel ratio, boost, injection spray, and compression ratio.

We have established a scientific framework to understand how bowl geometry can impact turbulent flow structure. Current CFD simulations are directed at understanding how vortex formation mechanisms are affected by various calibration parameters (see reviewer-only slide for details).

**The bowl geometry study should focus on efficiencies near or higher than the baseline, rather than late injections with poor efficiency.**

The project supports broader DOE goals of understanding how flows can be manipulated to improve efficiency and reduce emissions. The benefits of the stepped-lip piston associated with recirculating flow structures appear to diminish at more advanced injection timings. We're trying to understand how the physical mechanism changes with injection timing so we can make recommendations for a more robust combustion system with benefits that are less sensitive to injection timing.

**Now that the tools have been developed using the chosen piston profiles, can they be used to look at optimizing and ranking different bowl features with the ultimate goal being to provide guidance to the design process?**

Analysis tools are an essential part of this process, as they enable a fundamental understanding of how the fluid mechanics are impacted by various aspects of combustion system design and calibration. Understanding sensitivities to bowl features is a very important part of the work going forward, but we also need to understand how other parameters such as injection duration and spray targeting affect the mechanisms responsible for the benefits of stepped-lip pistons. The current plan is to continue using our calibrated CFD tools to learn as much as possible and to test theories about changes to piston design as understanding improves. We will develop experimental plans if the need arises. We are striving to provide guidance on combustion system design.

**Can the results of the bowl geometry study be confounded by geometry differences other than the stepped-lip?**

We haven't yet identified evidence that supports this idea. The results of this year's analysis suggest that a significant confounding factor of the injection timing sweep is the ambient density and its effect on air entrainment/ jet velocity distribution. Spray targeting and piston-head proximity play roles as well, and we will continue to work to understand exactly why the two pistons perform differently.

**Are the post-processing techniques specific to FRESKO or can they be used with other CFD software?**

While the methodology is generally applicable to any CFD results, the FRESKO post-processing toolbox currently only supports FRESKO output files. The differences in grid structure and data storage between various CFD platforms make it difficult to extend this tool to any arbitrary CFD output.

**The team should try to enlist more active participation from a technical expert in the combustion-fuel-system-air management to help guide the work toward a place where a significant breakthrough can be attained. Without this, it is likely that the team will continue to produce data of little relevance.**

We are open to collaborate with all interested experts in the field and participate in numerous discussions with industrial partners within the AEC MOU. The feedback about our current scientific approach to understanding the mechanisms that drive vortex formation has been positive and yielded helpful suggestions that have helped shape the proposed future work. Experts at Ford and GM continue to actively participate in discussions about piston bowl geometry effects and future directions of the research.



# Collaborations



Wisconsin Engine  
Research Consultants

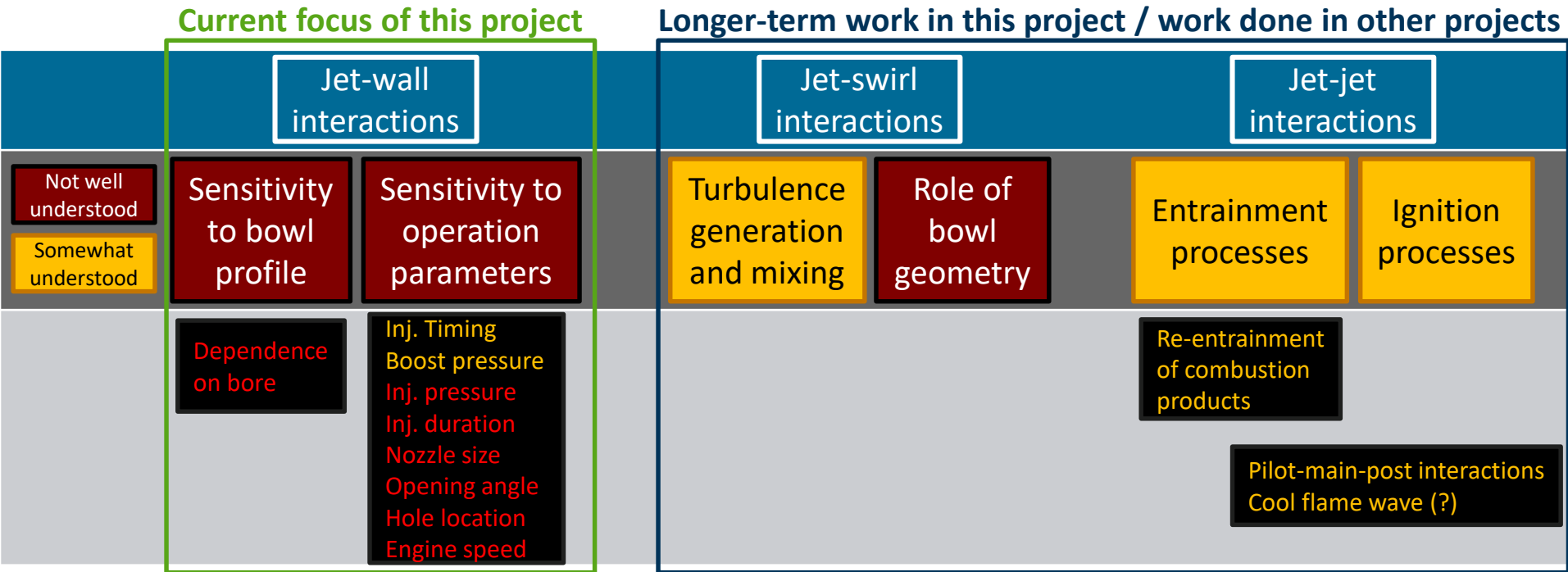


- **Wisconsin Engine Research Consultants – project subcontractor**
  - CFD simulations, numerical model development, post-processing support
  - This was formerly a subcontract with UW-Madison; the personnel working on the project have not changed
- **University of Wisconsin-Madison – university collaboration**
  - Full engine testing: catalyst heating operation, injection schedule calibration and operating parameter variations; impact on exhaust temperature/enthalpy and untreated pollutant emissions
  - Collaborative identification of operating points for optical study
- **Ford Motor Company – industry partner**
  - Technical advising on experimental parameters for catalyst heating screening study; collaborative analysis of exhaust emissions / temperature trends
  - Advice on parametric CFD studies with piston bowl geometry project
  - Co-authorship of publications
- **General Motors Company – industry partner**
  - Technical advising on injection strategies for catalyst heating operation
  - Advice on project direction
  - Co-authorship of publications
- **Cummins – industry partner**
  - CFD simulations using CONVERGE; collaborative comparison of simulation results to experimental data available on the ECN



# Progress and remaining elements required for a conceptual model of light/medium-duty diesel combustion

- A conceptual model of light- / medium-duty diesel combustion requires fundamental understanding of phenomena that occur differently than in an injection chamber or a heavy-duty engine
- This list of phenomena is not complete – the conceptual model is a work in progress
- Building the conceptual model requires collaboration within Sandia, with industry, and with other research organizations



# Proposed future work (1/2)

Any proposed future work is subject to change based on funding levels

## Bowl geometry study: continue with CFD simulations

- Parametric variations in the context of new understanding of vortex formation mechanisms
  - Ambient density, injector opening angle, boost pressure, injection velocity/flow rate/duration/pressure
- Combusting simulations
  - Evaluation of predictive performance in terms of efficiency and soot emissions through comparison with experimental results
- Piston bowl profile sensitivity study
  - Leverage understanding from above studies to develop parametric variations and new piston design features

## Catalyst heating study

- UW: characterization of tradeoffs and sensitivities between operating parameters and exhaust emissions/enthalpy
  - Post injection schedule/calibration, injection pressure, EGR rate
  - Identify conditions for which hydrocarbon and formaldehyde emissions decouple from one another
- SNL: development of capabilities to detect formaldehyde in-cylinder and in the exhaust
  - Assess optical PLIF technique to distinguish formaldehyde from PAH/other species
  - Assess infrared absorption technique to observe formaldehyde
  - Acquire / set up FTIR to measure formaldehyde in the exhaust
  - Apply new measurement capabilities to provide deeper insight into tradeoffs between emissions and exhaust enthalpy / decoupling of hydrocarbons and formaldehyde



# Proposed future work (2/2)

Any proposed future work is subject to change based on funding levels

## New medium-duty thermal and optical research engine

- The decision to change platforms was based on discussions with DOE program managers and Ford/GM in January of 2018
- Desired capabilities
  - ~100 mm bore with production cylinder head / port design
  - Dual engine configurations:
    - **Thermal** (all metal engine with metal piston rings for continuously-fired operation)
    - **Optical** (full optical access; optical pistons with production piston geometry)
- Intended timeframe
  - FY18: develop project roadmap / plan, start design and fabrication processes
  - FY19: commissioning of thermal engine configuration, followed by optical configuration
- Current status
  - Awaiting approval / funding allocation from DOE
  - Actively participating in discussions with Ford about collaborative development of a single-cylinder thermal/optical engine



# Summary

## Relevance

- Lack of fundamental understanding of spray-wall interaction mechanisms that create beneficial flow structures is a barrier to combustion system development
- Mechanisms responsible for tradeoffs between exhaust temperature/enthalpy, efficiency, and criteria pollutant emissions, and their sensitivities to catalyst heating operating strategies are not well understood

## Approach

- Piston bowl geometry study continues as a CFD study with W-ERC as a subcontractor; ongoing simulations and analyses focus on understanding mechanisms that create beneficial flow structures and their sensitivity to various combustion system design and calibration parameters
- A working group has been established for the catalyst heating study; diagnostic and measurement capabilities are being developed at SNL; ongoing experiments will help identify relevant conditions for further study

## Technical Accomplishments

- A quantitative database including engine geometry and boundary conditions is now available on the ECN website
- Combustion image velocimetry provides evidence of unique recirculating flow structures that correspond to improved air utilization / thermal efficiency with the stepped-lip combustion chamber
- Analysis of FRESKO CFD simulations yields new understanding of how spray-step interactions create beneficial flow structures, and of the sensitivities of this mechanism to injection timing and ambient density

## Collaborations

- **Subcontract with WERC** (formerly with UW-Madison; no change in personnel): CFD simulations using FRESKO
- **GM, Ford:** technical advising; frequent communication about catalyst heating operation; potential collaborative development of new single-cylinder engine
- **Cummins:** collaborative evaluation of CFD capabilities using CONVERGE

## Future Work

- **Bowl geometry study:** continue with CFD; parametric studies involving stepped-lip piston
- **Cat heating operation:** development of capabilities, search for decoupling of HC/CH<sub>2</sub>O, begin optical diagnostics
- **New medium-duty diesel research platform:** pending funding decisions by DOE

