SAND2018-4276PE

Light- and Medium-Duty Diesel Combustion

Stephen Busch - Principal Investigator

Sandia National Laboratories

June 19, 2018

Program Managers:
Gurpreet Singh, Mike Weismiller

Project ID: ACS002

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

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: $200k
- Subcontract with UW: $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_2O / NO_x / 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_2O 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

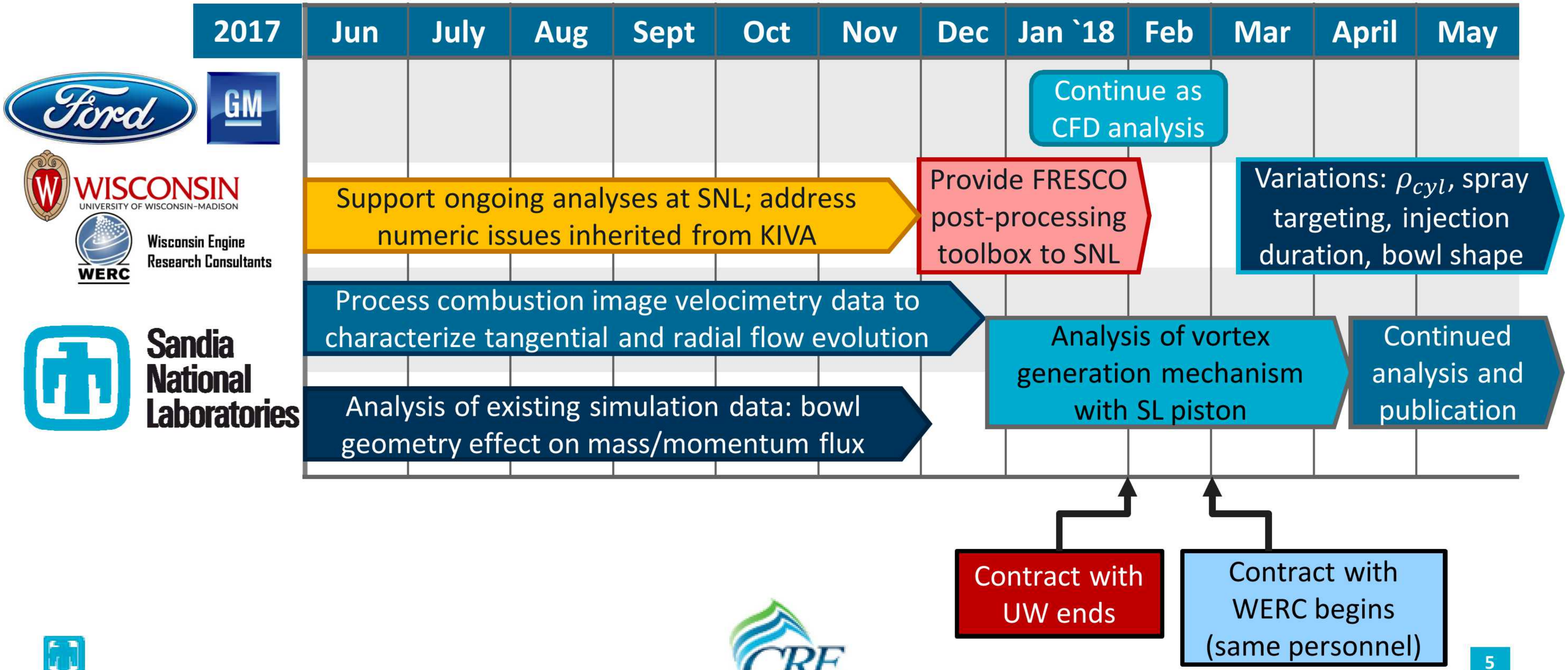
[3] Mercuri, D., Pozzi, C., Natì, G., Cassani, S., "Multi-After Injection Strategy to Optimize Exhaust Gases Temperature and Combustion Stability in Diesel Engine," presented at 24th Aachen Colloquium Automobile and Engine Technology, Aachen, Germany, October 5-7, 2015

[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
- FRESCO post-processing toolbox has helped create a framework to understand ongoing parametric studies and shape future bowl shape sensitivity studies



2017 | Jun | July | Aug | Sept | Oct | Nov | Dec | Jan `18 | Feb | Mar | April | May

Ford, GM: Continue as CFD analysis

Wisconsin (University of Wisconsin–Madison), Wisconsin Engine Research Consultants (WERC):

- Support ongoing analyses at SNL; address numeric issues inherited from KIVA
- Provide FRESCO post-processing toolbox to SNL
- Variations: ρ_{cyl}, spray targeting, injection duration, bowl shape

Sandia National Laboratories:

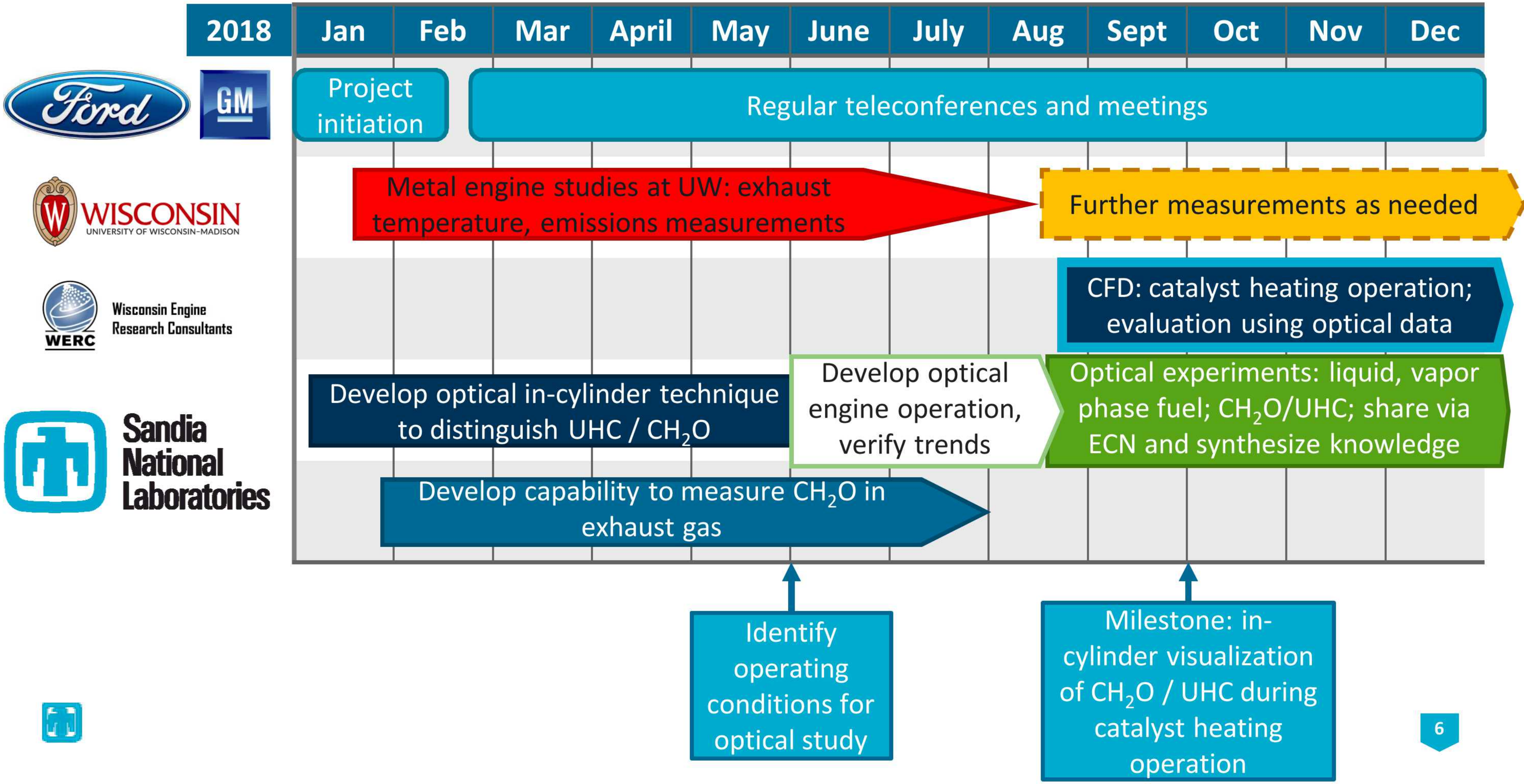
- Process combustion image velocimetry data to characterize tangential and radial flow evolution
- Analysis of existing simulation data: bowl geometry effect on mass/momentum flux
- Analysis of vortex generation mechanism with SL piston
- Continued analysis and publication

Contract with UW ends

Contract with WERC begins (same personnel)

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)



Project initiation

Regular teleconferences and meetings

Metal engine studies at UW: exhaust temperature, emissions measurements

Further measurements as needed

CFD: catalyst heating operation; evaluation using optical data

Develop optical in-cylinder technique to distinguish UHC / CH$_2$O

Develop optical engine operation, verify trends

Optical experiments: liquid, vapor phase fuel; CH$_2$O/UHC; share via ECN and synthesize knowledge

Develop capability to measure CH$_2$O in exhaust gas

Identify operating conditions for optical study

Milestone: in-cylinder visualization of CH$_2$O / UHC during catalyst heating operation

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 combusting 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**

CRF

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

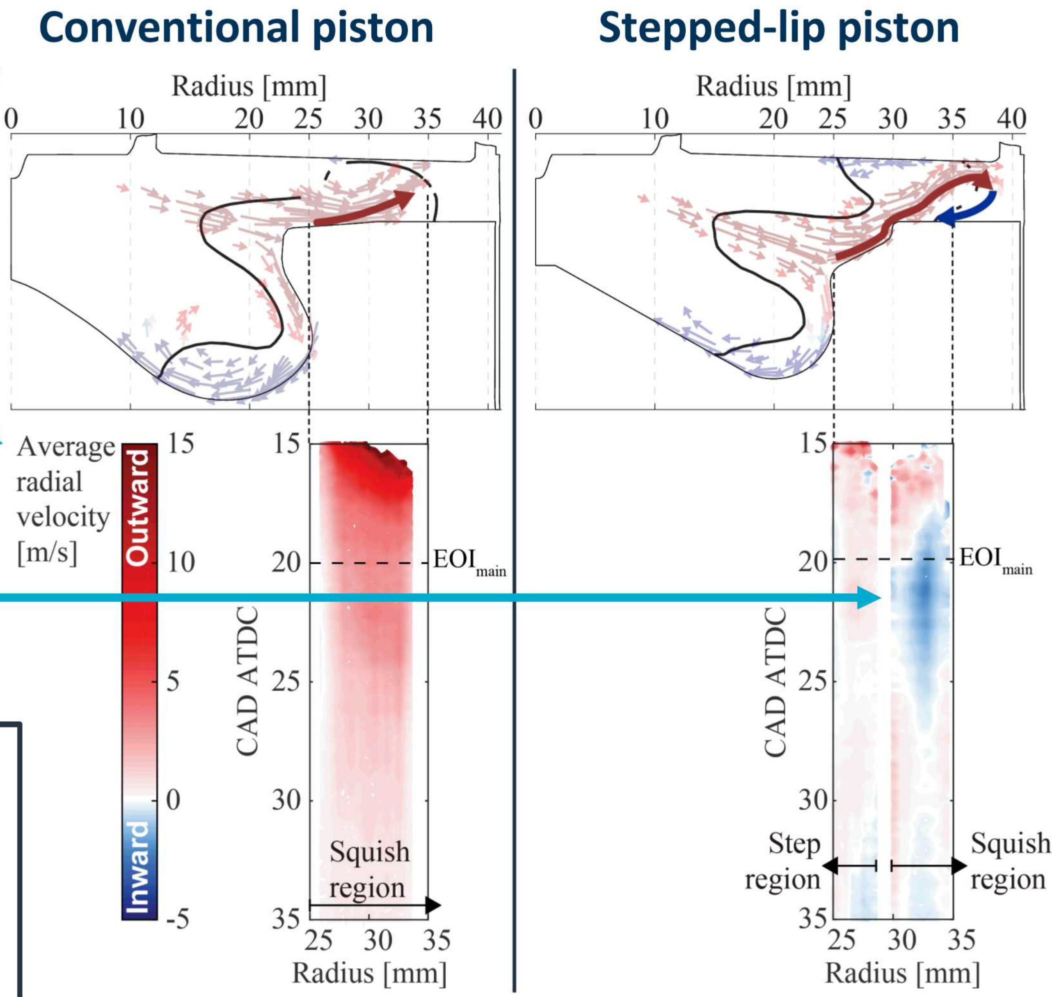
- Ongoing discussions focus on making meaningful comparisons between experimental data and CFD results
  - There are currently no plans to adapt the FRESCO postprocessing toolbox to enable analysis of CONVERGE results

- 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

Insert image exemplifying the results of the CFD calibration efforts here

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

- 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



Conventional piston

Stepped-lip piston

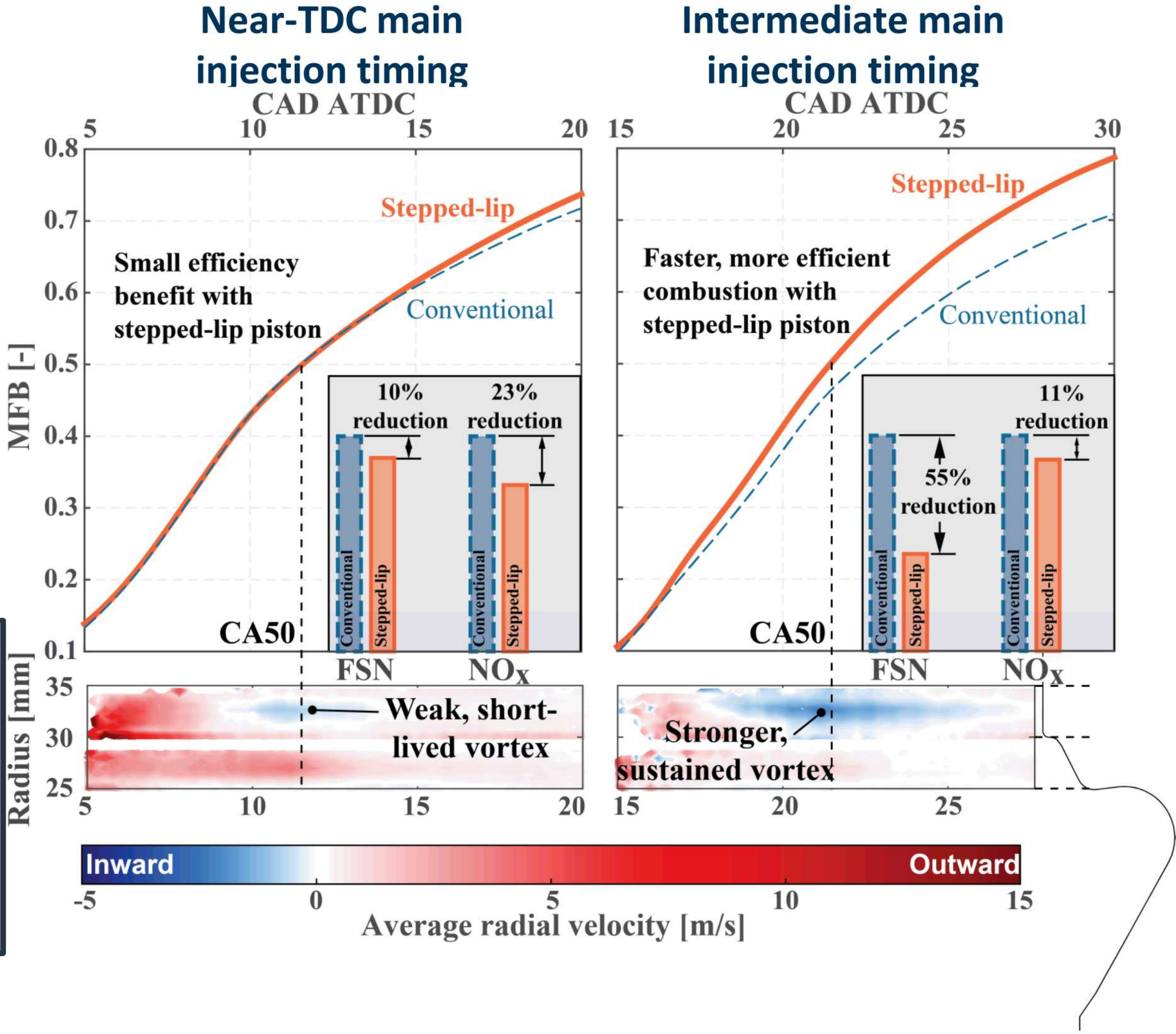
- This first experimental characterization of in-cylinder flow during mixing-controlled combustion with both pistons provides:
  - **Improved understanding of how bowl geometry influences flow structure**
  - **Quantitative dataset for collaborative CFD code validation (available via ECN)**

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]

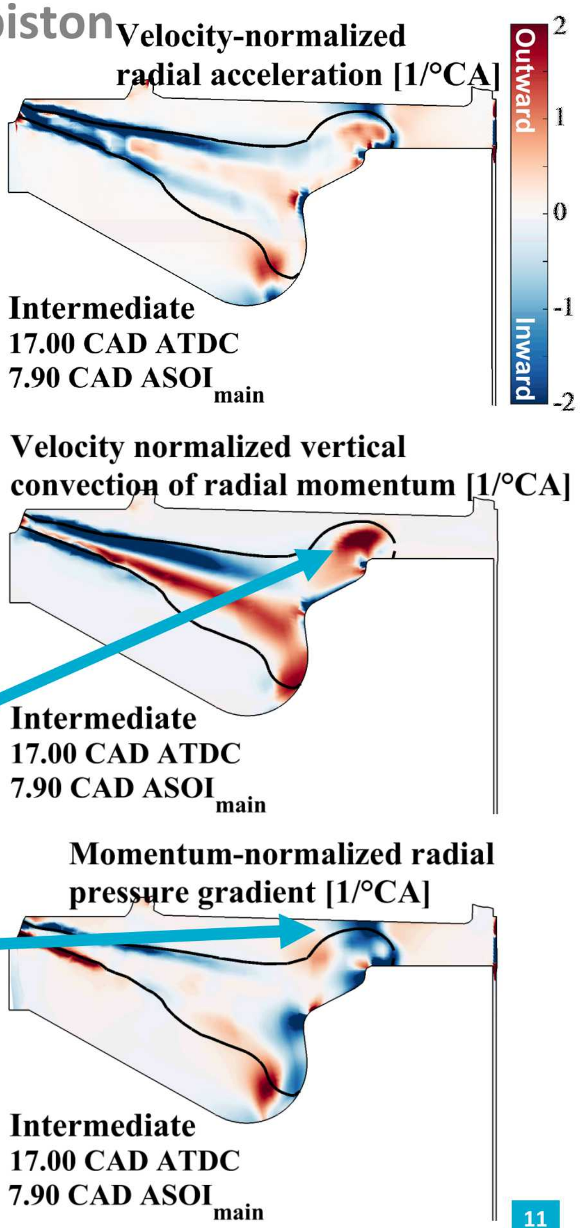
- Flow structures associated with emissions and efficiency benefits are sensitive to injection timing
  - **Further efficiency and emissions improvements may be realized if these vortices can be strengthened at near-TDC injection timings**



[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 FRESCO 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**



Velocity-normalized radial acceleration [1/°CA]

Intermediate
17.00 CAD ATDC
7.90 CAD ASOI$_{main}$

Velocity normalized vertical convection of radial momentum [1/°CA]

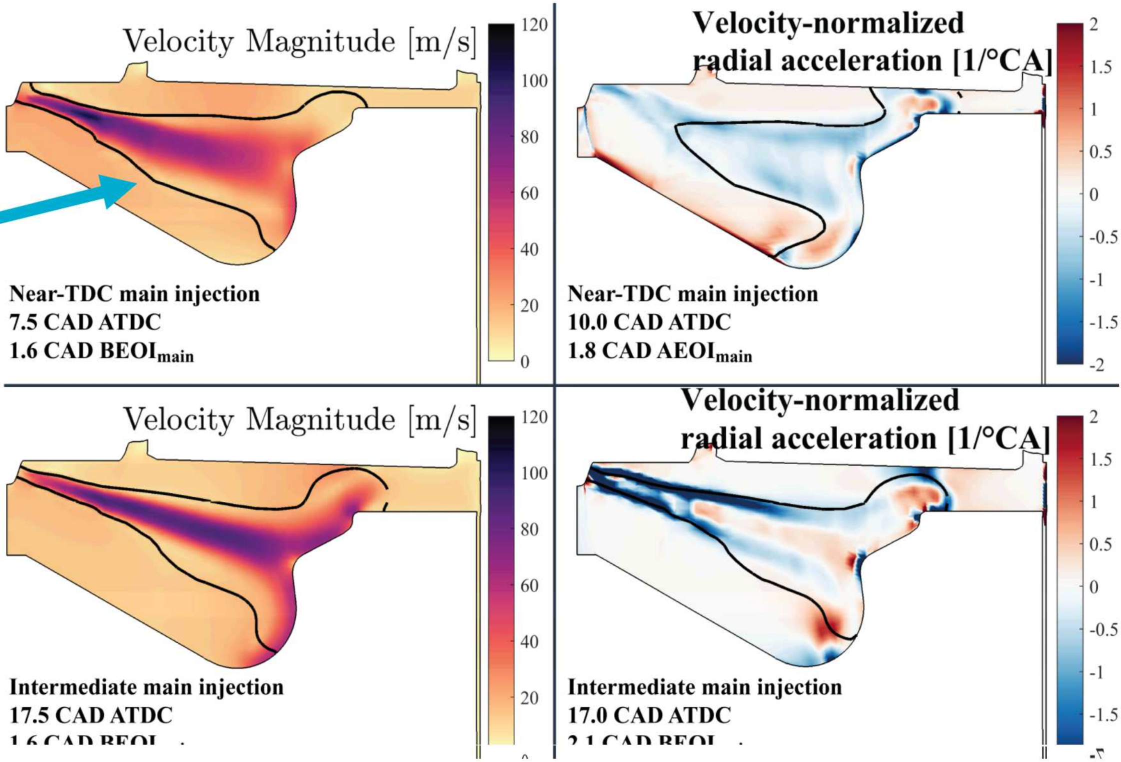
Intermediate
17.00 CAD ATDC
7.90 CAD ASOI$_{main}$

Momentum-normalized radial pressure gradient [1/°CA]

Intermediate
17.00 CAD ATDC
7.90 CAD ASOI$_{main}$

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

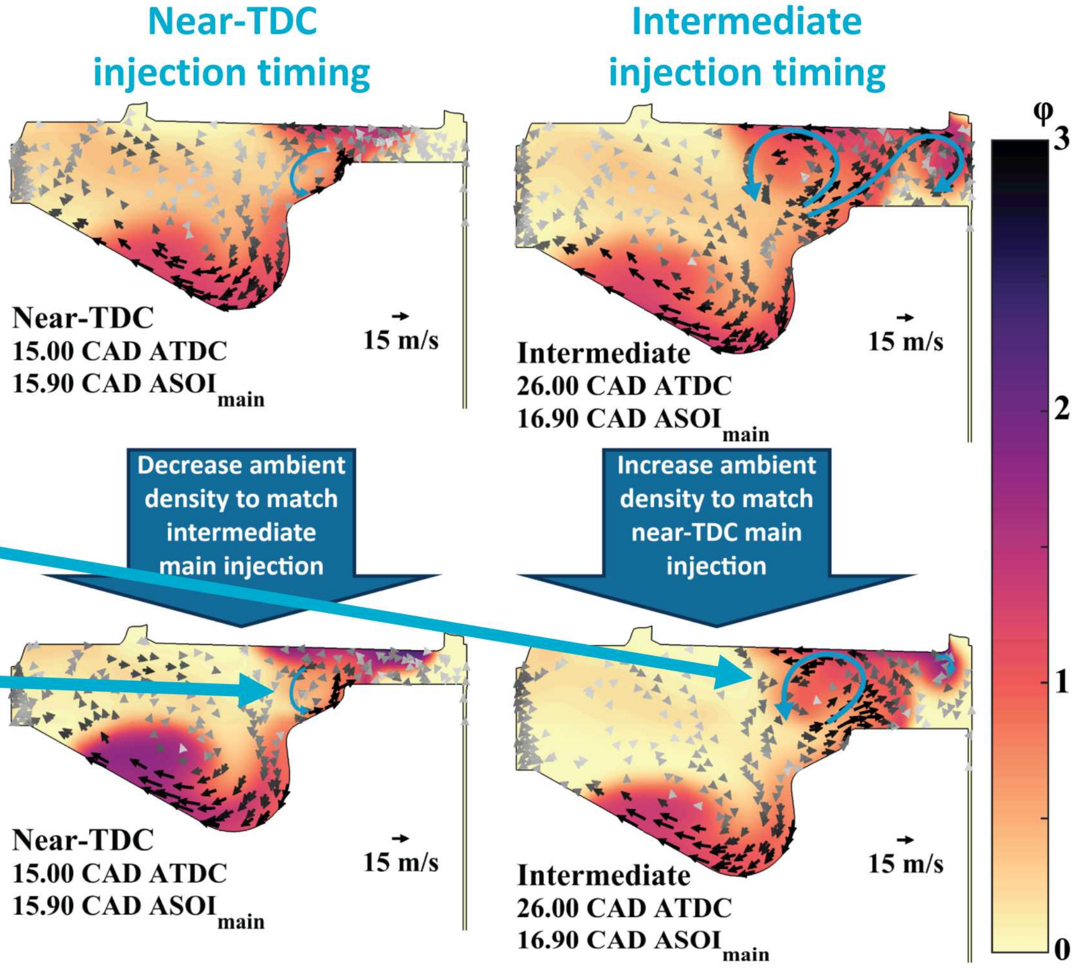
- Ambient density changes with injection timing and affects air entrainment, jet structure, and penetration velocity
- For injection timings closer to TDC, the jets entrain more air and penetrate more slowly
  - Near-TDC injection timing: secondary jet separates from the piston surface after the end of injection ($\text{AEOI}_{\text{main}}$)
- 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 FRESCO 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



Decrease ambient density to match intermediate main injection

Increase ambient density to match near-TDC main injection

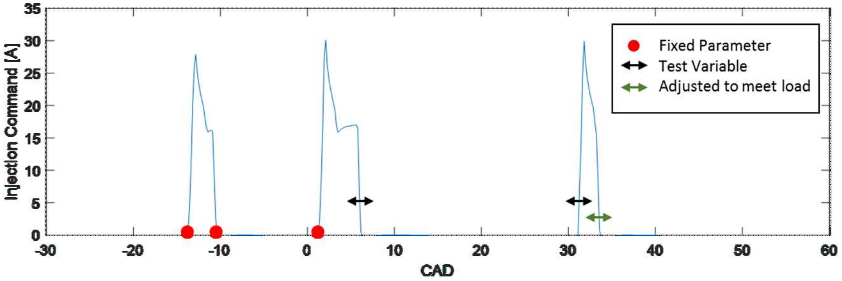
TA: initial characterization of GM 1.9L engine in catalyst heating operation at UW-Madison

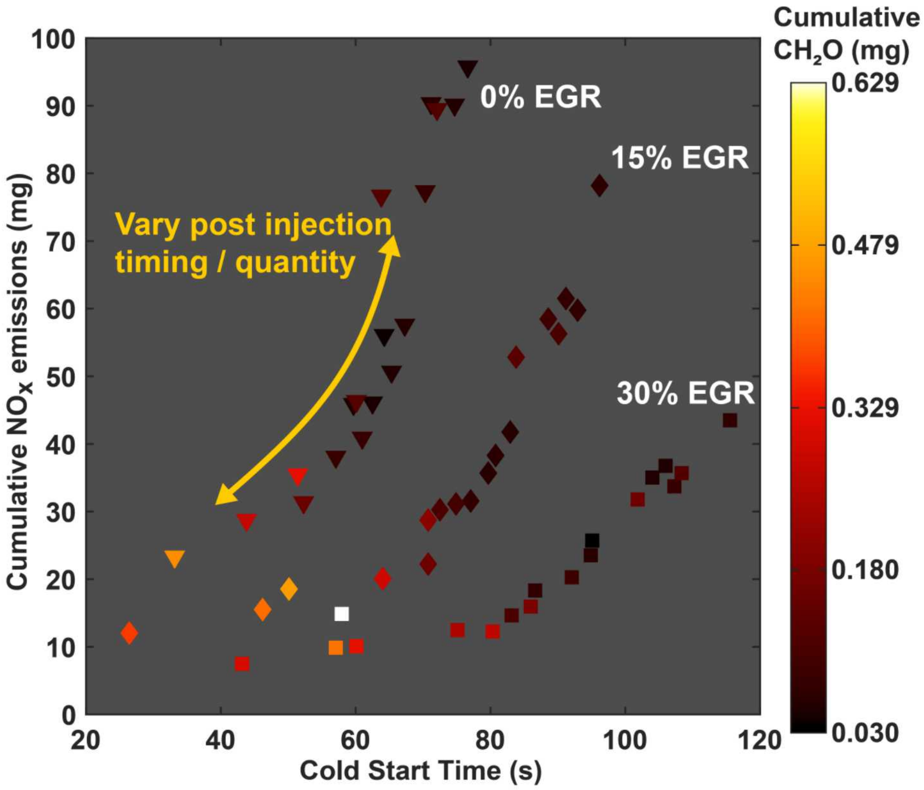
- Preliminary characterization of the GM 1.9L combustion system is complete for a pilot-main-post injection strategy

- 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 NO_x (y-axis), CH_2O 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 FRESCO or can they be used with other CFD software?

> While the methodology is generally applicable to any CFD results, the FRESCO post-processing toolbox currently only supports FRESCO 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.

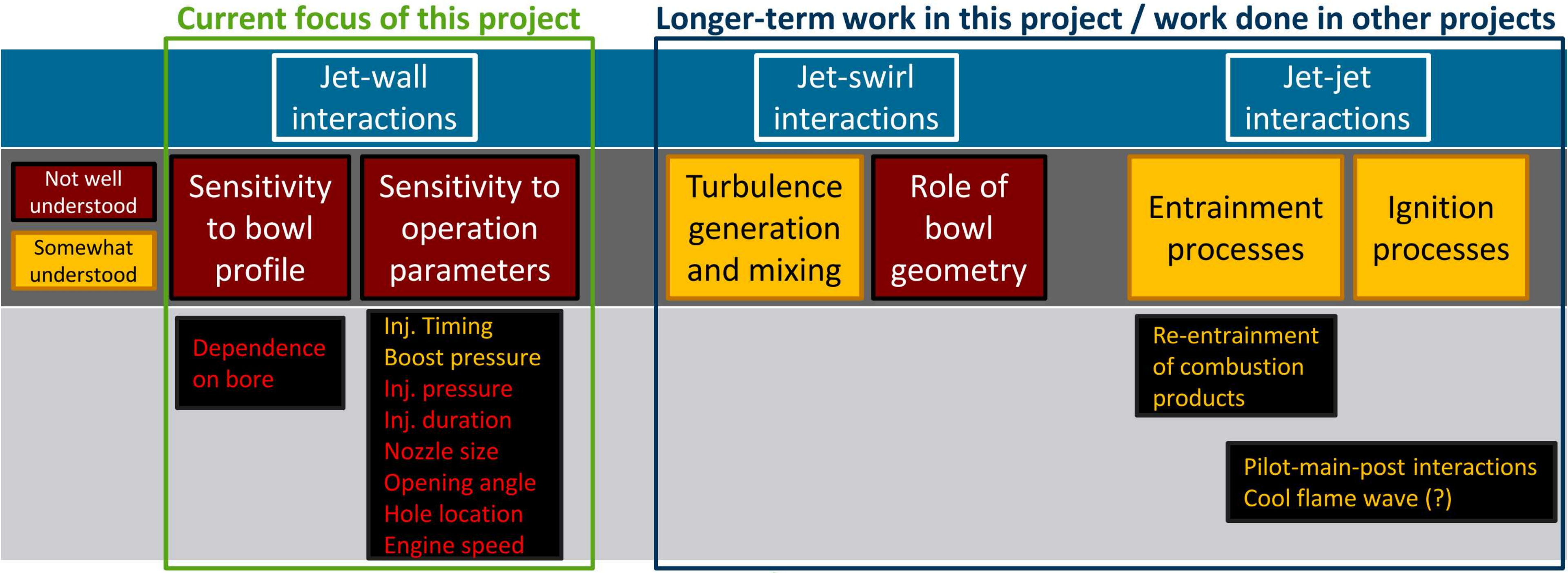
> We are open to collaborate with all interested experts in the field and participate in numerous discussions with industrial partners within the AEC MOU. The feedback about our current scientific approach to understanding the mechanisms that drive vortex formation has been positive and yielded helpful 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** – 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



Current focus of this project

Longer-term work in this project / work done in other projects

Not well understood

Somewhat understood

Jet-wall interactions

Sensitivity to bowl profile

Dependence on bore

Sensitivity to operation parameters

Inj. Timing
Boost pressure
Inj. pressure
Inj. duration
Nozzle size
Opening angle
Hole location
Engine speed

Jet-swirl interactions

Turbulence generation and mixing

Role of bowl geometry

Jet-jet interactions

Entrainment processes

Re-entrainment of combustion products

Ignition processes

Pilot-main-post interactions
Cool flame wave (?)

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 FRESCO 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 FRESCO
- **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/CH2O, begin optical diagnostics
- **New medium-duty diesel research platform**: pending funding decisions by DOE

Reviewer-Only Slides

Publications and Presentations

- Publications
  - Perini, F., Zha, K., Busch, S., Kurtz, E., Peterson, R.C., Warey, A., Reitz, R.D., "Piston geometry effects in a light-duty, swirl-supported diesel engine: flow structure characterization", International Journal of Engine Research Online First, 2017, doi:10.1177/1468087417742572.
  - Busch, S., Zha, K., Kurtz, E., Warey, A. and Peterson, R. C., "Experimental and Numerical Studies of Bowl Geometry Impacts on Thermal Efficiency in a Light-Duty Diesel Engine," SAE Technical Paper 2018-01-0228, 2018, DOI: 10.4271/2018-01-0228.
  - Zha, K., Busch, S., Warey, A., Peterson, R. C. and Kurtz, E., "A Study of Piston Geometry Effects on Late-Stage Combustion in a Light-Duty Optical Diesel Engine Using Combustion Image Velocimetry," SAE Technical Paper 2018-01-0230, 2018, DOI: 10.4271/2018-01-0230.

- Presentations
  - Busch, S., Zha, K., Perini, F., Reitz, R., “Piston Bowl Geometry Impacts on Late-Cycle Flow and Mixing in a Small-Bore Diesel Engine,” Presented at AEC Program Review Meeting. Southfield, Michigan, August 23, 2017.
  - Perini, F., Busch, S., Reitz, R., “Automatic optimal mesh handling for Internal Combustion Engine Simulations,” Presented at AEC Program Review Meeting. Southfield, Michigan, August 23, 2017.
  - Busch, S., Zha, K., Perini, F., Reitz, R., “Progress Toward Understanding Injection Timing Sensitivity with Stepped-Lip Diesel Piston Bowls,” Presented at AEC Program Review Meeting. Lemont, Illinois, January 30, 2018.

Critical assumptions and issues

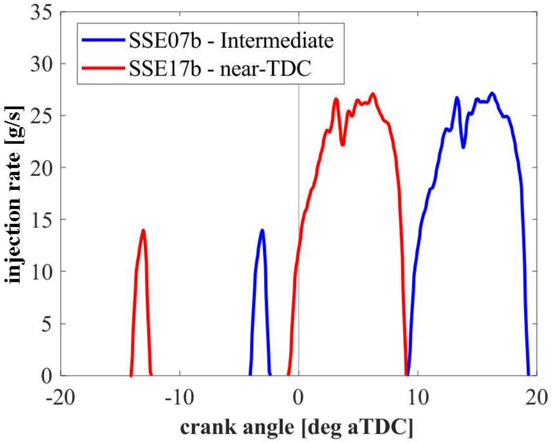
- Operation with late injection timings (such as the intermediate injection timing used in the bowl geometry study) is non-optimal in terms of efficiency. Why is the analysis focused on comparing this point to a more efficient injection timing, where both the stepped-lip and conventional combustion chambers behave nearly the same?
  - The stepped-lip piston provides clear advantages in efficiency and air utilization at the intermediate injection timing. Providing fundamental understanding of the mechanisms responsible for these advantages, and why they aren't available at more advanced injection timings, will provide the basis needed to realize these advantages at more advanced, efficient injection timings.

- What is the purpose of using an optical engine to study catalyst heating operation?
  - Optical experiments will provide quantitative datasets to evaluate CFD simulations and develop new modeling approaches with complex injection strategies under atypical ambient conditions. Improving our understanding of tradeoffs between formaldehyde, hydrocarbons, NOx, soot, exhaust enthalpy, and efficiency will require a sustained collaboration between experiments and simulations. The ability to distinguish between formaldehyde and other hydrocarbons in-cylinder may provide valuable insight into mechanisms responsible for decoupling of engine-out hydrocarbon and formaldehyde emissions.

Considerations for standard diesel operating point

Parameter`	Value	Rationale
Engine speed	1500 rpm	Optimal speed for skip-fired operation of optical engine; other speeds may be better investigated with CFD
IMEPg	9 bar	Many competing factors that pose challenges to diesel engine calibration are in play at this load: soot, NOx, and combustion noise. This is close to the highest load that can safely be studied in the optical engine. Injection duration (load) will be varied/investigated in upcoming CFD studies.
Injection pressure	800 bar	This is close to the production rail pressure for the GM 1.9L combustion system; its impact will be investigated in upcoming CFD studies
Swirl ratio	2.2	This swirl ratio is achieved with no throttling of either intake port; it is the default swirl ratio of the GM 1.9L combustion system
EGR rate	7% + 3.3% internal residual	This EGR rate is appropriate for the GM 1.9L combustion system at this load
Injection strategy	Pilot-main	Pilot injection enables exploration of a wide range of injection timings; the single pilot-main strategy avoids the complication of calibrating more complex injection strategies
Pilot quantity	1.4-1.5 mg/str	This quantity ensures reliable ignition of the main injection
Pilot-main dwell	1200 µs	This dwell avoids rail pressure dynamics issues
Main injection duration	Approximately 10 CAD, depends on injection timing	This is the injection duration required to reach the target load with the near-production fuel injector in this engine; injector flow rate parameters (hole size, injection pressure) will be varied in upcoming CFD studies

Ongoing CFD parametric variation: ambient density at SOI_{main}



	Near-TDC	Intermediate
SOI_{main} [deg aTDC]	-0.86	9.05
p_{SOI} [bar]	51.44	43.45
ρ_{SOI} [kg/dm³]	19.50	17.60
T_{SOI} [K]	890.9	833.28
V_{SOI} [cm³]	35.0	38.9
p_{IVC} [bar]	1.64	1.64
ρ_{IVC} [kg/dm³]	1.52	1.52
T_{IVC} [K]	363.6	363.8
V_{IVC} [cm³]	448.0	448.0
γ	1.352	1.341

- Decoupling ambient density effects: change intake pressure
  - Near-TDC injection timing: decrease charge density at SOI_{main} to match intermediate injection timing case
  - Intermediate injection timing: increase charge density at SOI_{main} to match near-TDC injection timing case

Assuming constant γ and neglecting the change in mass due to pilot injection:

$$p_{IVC}V_{IVC}^{\gamma} = p_{SOI}V_{SOI}^{\gamma} \quad \Rightarrow \quad \gamma = \frac{\log\left(\frac{p_{SOI}}{p_{IVC}}\right)}{\log\left(\frac{V_{IVC}}{V_{SOI}}\right)}$$

In an isentropic process,

$$\rho_{IVC}V_{IVC} = \rho_{SOI}V_{SOI}$$

- Near-TDC: $\rho_{IVC} = \frac{V_{SOI}}{V_{IVC}}\rho_{SOI,SSE07} = 1.375\,\frac{kg}{dm^3}$

$$p_{IVC} = 1.432\ bar$$
$$\Delta p_{IVC} = -0.208\ bar$$

- Intermediate: $\rho_{IVC} = \frac{V_{SOI}}{V_{IVC}}\rho_{SOI,SSE17} = 1.693\,\frac{kg}{dm^3}$

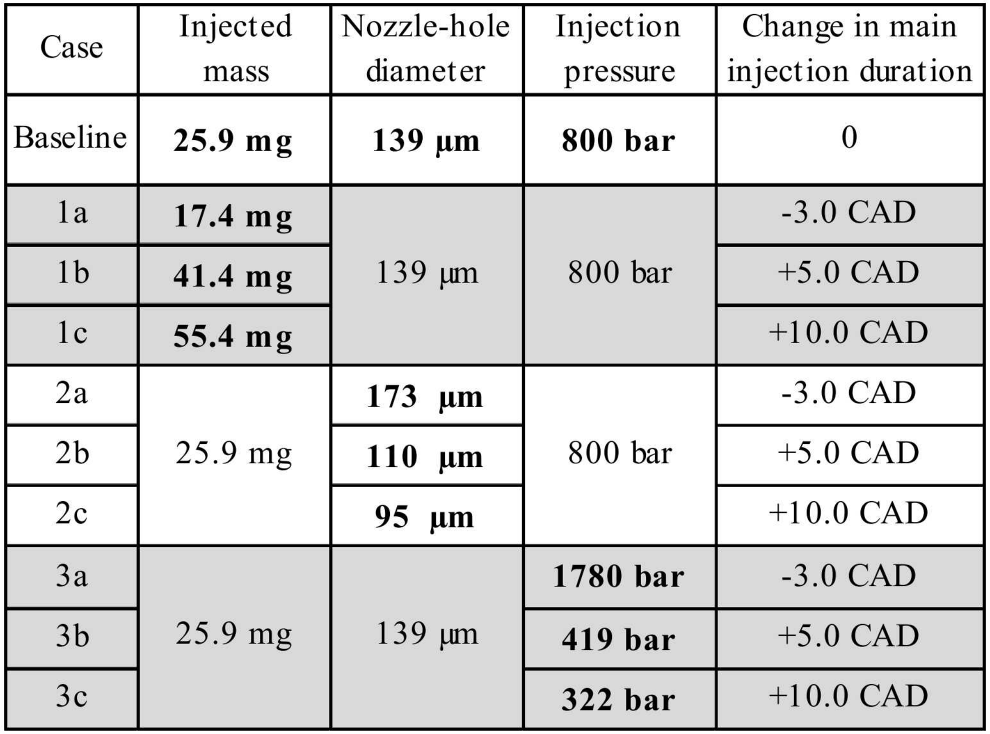
$$p_{IVC} = 1.895 bar$$
$$\Delta p_{IVC} = +0.255\ bar$$

Actual ambient densities at SOI_{main}

Case	ρ_{SOI} [kg/m³]
Near-TDC, baseline	19.5
Intermediate, ρ↑	20.1
Intermediate, baseline	17.6
Near-TDC, ρ↓	17.3

Planned CFD parametric variation: injection duration

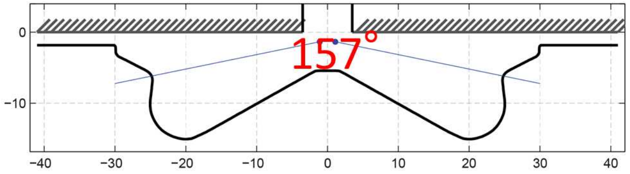
1. Injected mass variation: Injection pressure and nozzle-hole size are constant. Injection duration is varied around its baseline.
   - Effect: load change
2. Nozzle hole size variation: Injection pressure constant and injection duration varies as above. The nozzle hole size changes to maintain the same injected fuel mass for each case.
   - Effect: injector flow rate
3. Rail pressure variation: Nozzle-hole size is constant and injection duration varies as above. Injection pressure (injection velocity) is decreased to maintain the same injected fuel mass for each case.
   - Effect: jet velocity



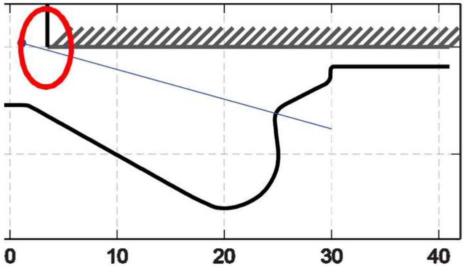
Case	Injected mass	Nozzle-hole diameter	Injection pressure	Change in main injection duration
Baseline	**25.9 mg**	**139 µm**	**800 bar**	0
1a	**17.4 mg**	139 µm	800 bar	-3.0 CAD
1b	**41.4 mg**			+5.0 CAD
1c	**55.4 mg**			+10.0 CAD
2a	25.9 mg	**173 µm**	800 bar	-3.0 CAD
2b		**110 µm**		+5.0 CAD
2c		**95 µm**		+10.0 CAD
3a	25.9 mg	139 µm	**1780 bar**	-3.0 CAD
3b			**419 bar**	+5.0 CAD
3c			**322 bar**	+10.0 CAD

Planned CFD parametric variation: spray targeting

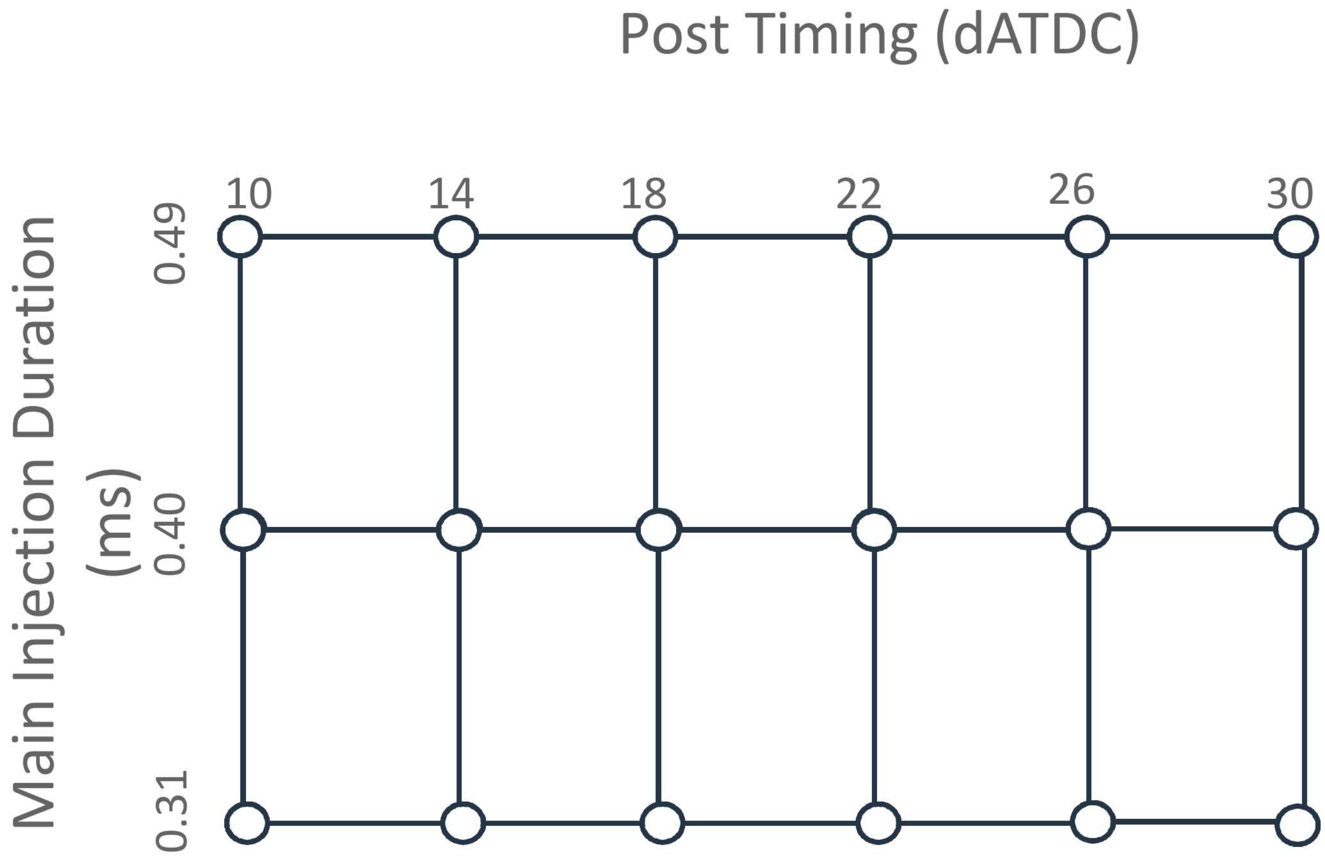
- Change spray targeting at near-TDC injection timing to match targeting at intermediate injection timing: two possibilities
  - Vary injector opening angle: 149˚(baseline), 153˚, 157˚:



  - Raising the injector height is not feasible due to probable jet-head interference:


Matching intermediate spray targeting for the near-TDC injection timing

Catalyst heating operation – pilot-main-post injection strategy



Sweeping post timing and main duration

Adjusting fueling in post injection to maintain load

0, 15, and 30% EGR

BMEP (bar)	2
Speed (rev/min)	1500
Rail Pressure (bar)	500
Main SOI (dATDC)	0
Pilot SOI (dATDC)	-15
Pilot qty (mg)	1.5 (.31ms)
Post SOI (dATDC)	10-30