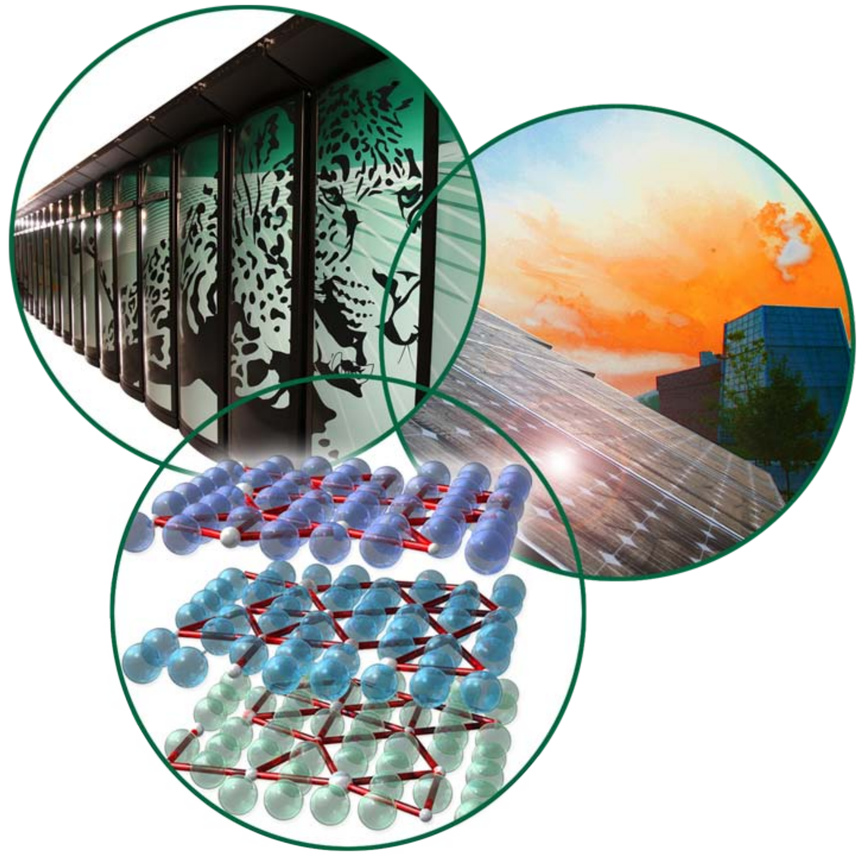
Load Expansion of Stoichiometric HCCI Using Spark Assist and Hydraulic Valve Actuation



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U.S. DEPARTMENT OF ENERGY

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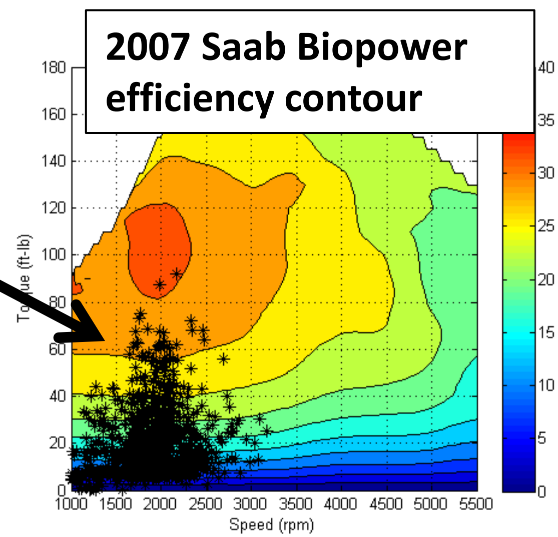
DEER 2010
DETROIT
DIRECTIONS IN ENGINE-EFFICIENCY AND EMISSIONS RESEARCH CONFERENCE

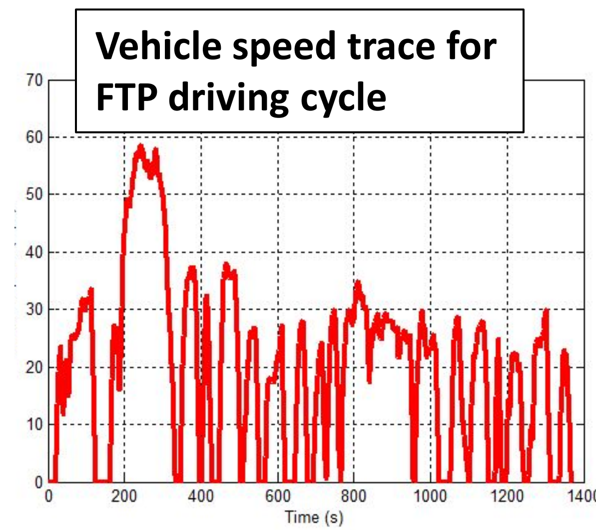
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Purpose of advanced combustion strategies in gasoline engines: improve efficiency without increasing tailpipe-out emissions

- **Tailpipe-out emissions are extremely low for gasoline engines due to mature 3-way catalyst exhaust aftertreatment at stoichiometric conditions**
- **Advanced combustion techniques must provide improved efficiency while not increasing tailpipe-out emissions**
  - **Either extremely low NOx or stoichiometric operation to maintain compatibility with a 3-way catalyst**
- **To have largest impact, advanced combustion strategies must be applicable over portion of engine map where engine operates most**

Data markers from FTP driving cycle overlaid on efficiency contour

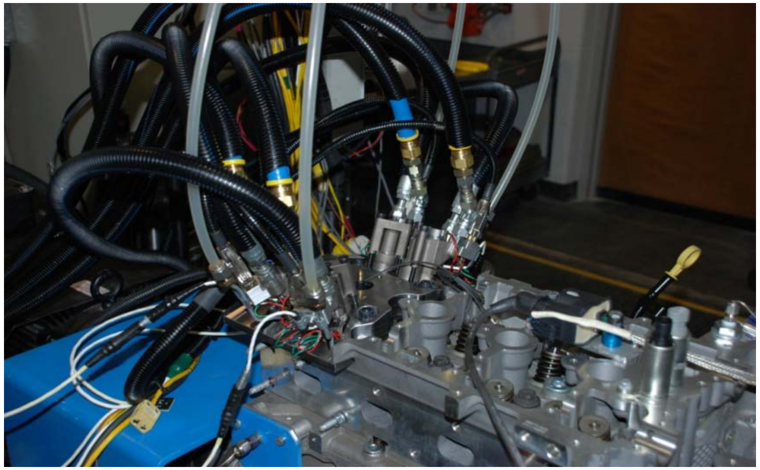




Previously unpublished data collected at ORNL's chassis lab facility.
Thanks to Brian West and others.

Single cylinder research engine with Sturman hydraulic valve actuation (HVA)

- Modified 2.0L GM Ecotec engine with direct injection
- Cylinders 1-3 are disabled, cylinder 4 modified for Sturman HVA system
- Engine management performed with Drivven engine controller
- Custom pistons to increase compression ratio
- UTG-96 certification gasoline



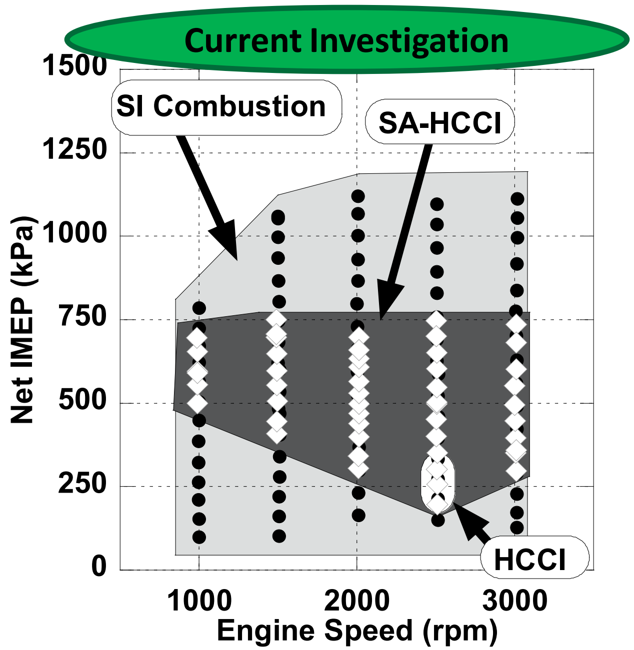
Bore	86 mm
Stroke	86 mm
Connecting Rod	145.5 mm
Fueling	Direct Injection
Compression Ratio	11.85
Valves per Cylinder	4

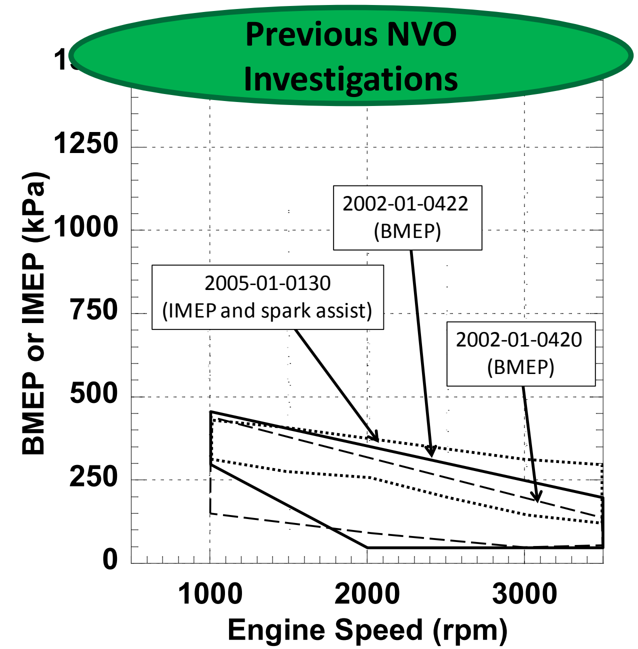
	SI Combustion	SA-HCCI
Fuel Rail Pressure (bar)	95	95
Fuel Injection Timing (CA)*	-280	-340
Equivalence Ratio	1.0	1.0
Intake Valve Opening (CA)*	-344	-313 to -234
Intake Valve Closing (CA)*	-180	-180 to -124
Intake Valve Lift (mm)	9	3 to 6
Exhaust Valve Opening (CA)*	180	170
Exhaust Valve Closing (CA)*	349	234 to 313
Exhaust Valve Lift (mm)	9	2 to 3.5
*0 CA refers to combustion TDC		

9.20 CR

11.85 CR

High load limit increased to 7.5 bar from 1000 to 3000 rpm with operating strategy



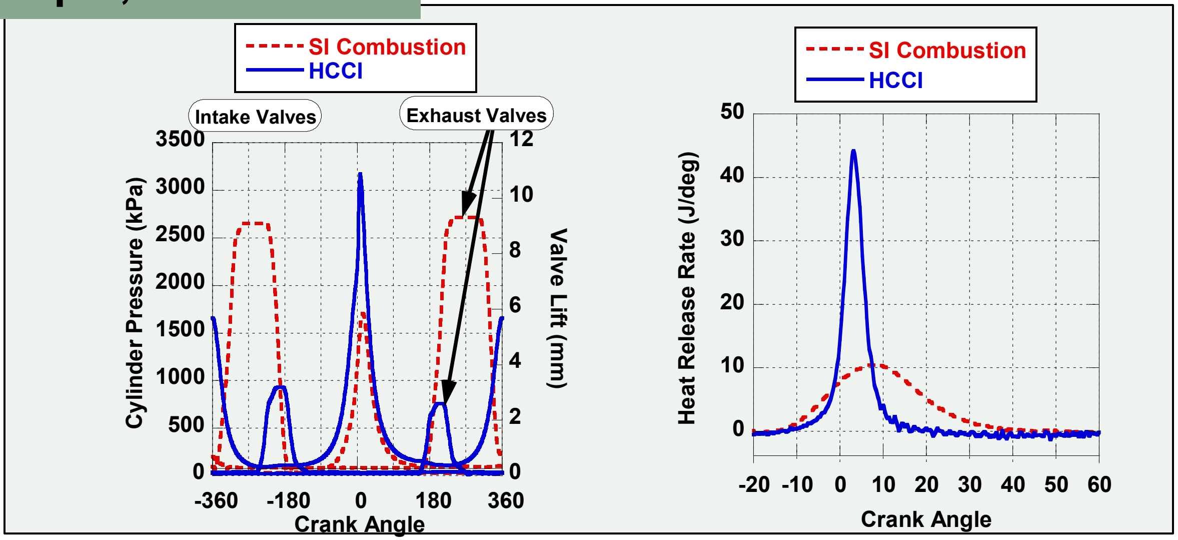


Attributes of the advanced combustion strategy

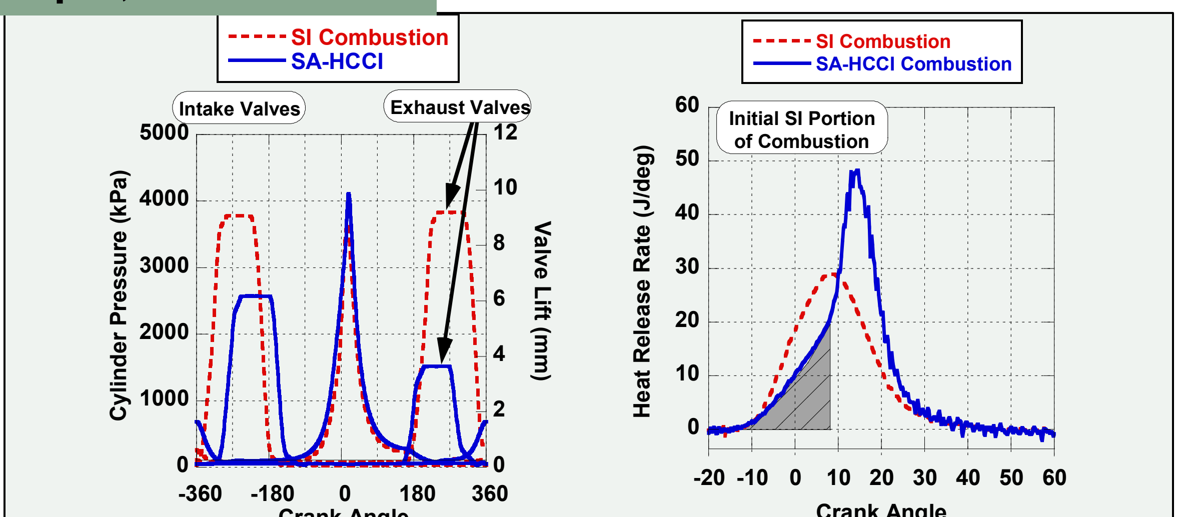
- Stoichiometric A/F ratio
- Spark assist
- Negative valve overlap for internal
  - No external EGR
- Unthrottled operation
- Variable intake valve closing angle to control effective compression ratio

Combustion analysis reveals role of spark assist

2500 rpm, 2 bar IMEP



2500 rpm, 6.5 bar IMEP

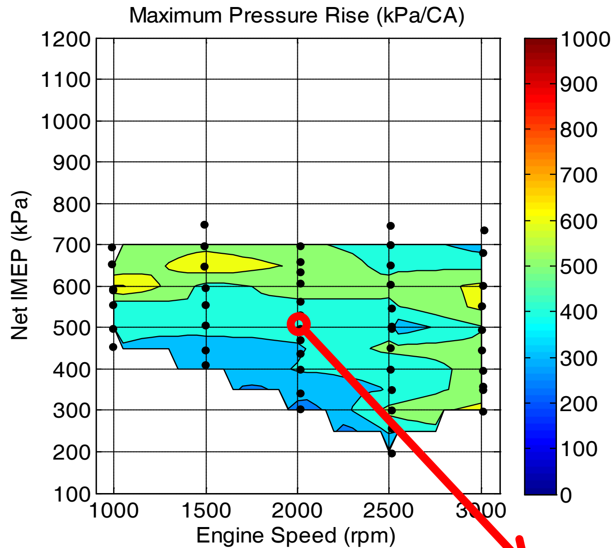


- By retarding spark timing and intake valve closing angle as load increases, pressure rise rate can be controlled to < 7bar/deg at all points
- Under light-load conditions, combustion event is dominated by volumetric combustion
- As engine load increases, a larger portion of the heat release occurs during the spark-ignited portion of combustion

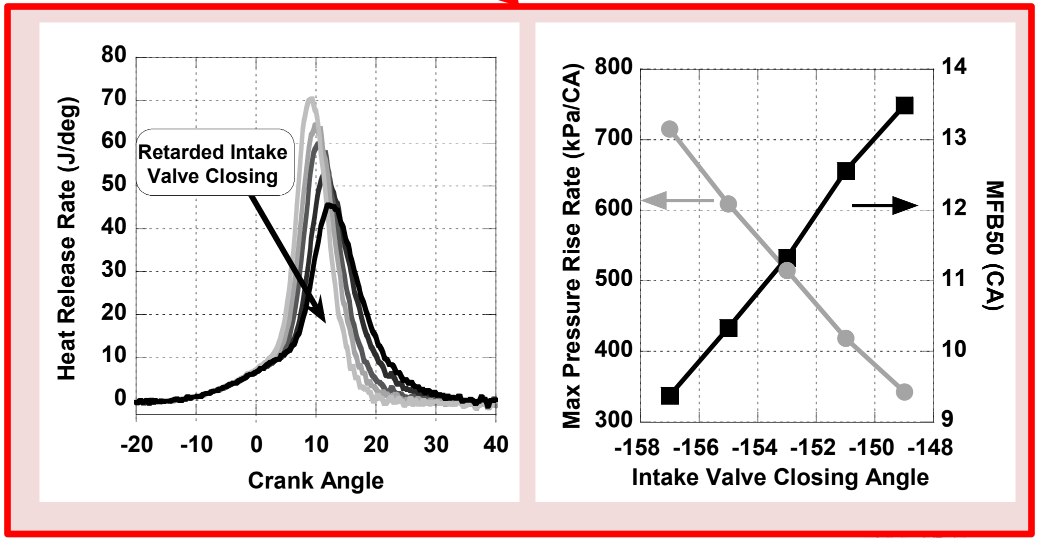
Late intake valve closing allows control of maximum pressure rise rate

- Retarding intake valve closing reduces the effective compression ratio
  – Similar to technique using late intake valve closing angle to mitigate knock demonstrated during ethanol optimization work*
  – Effective CR varied from 11.85:1, which is the geometrical compression ratio, to 10:1
- Some tradeoff exists between spark timing and intake valve closing angle

*For Example see SAE 2010-01-0619

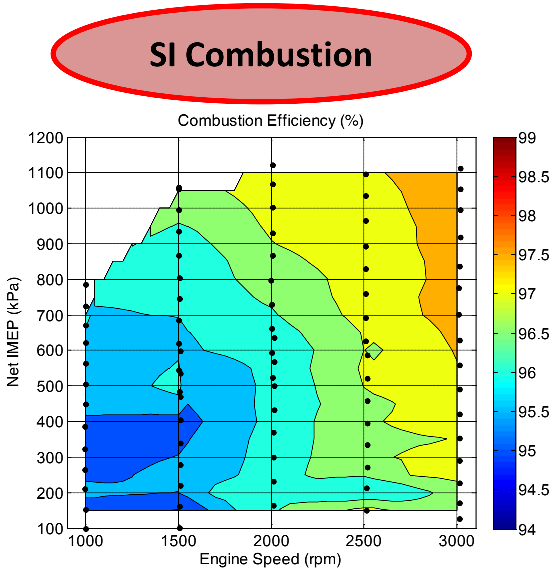


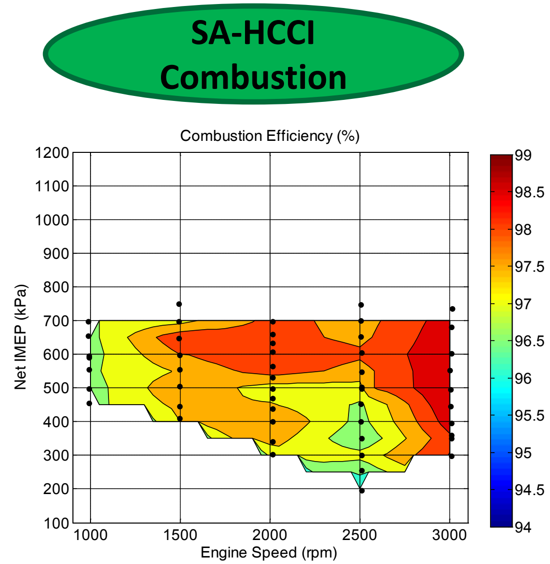
Sweep of intake valve closing angle 2000 rpm, 5 bar IMEP

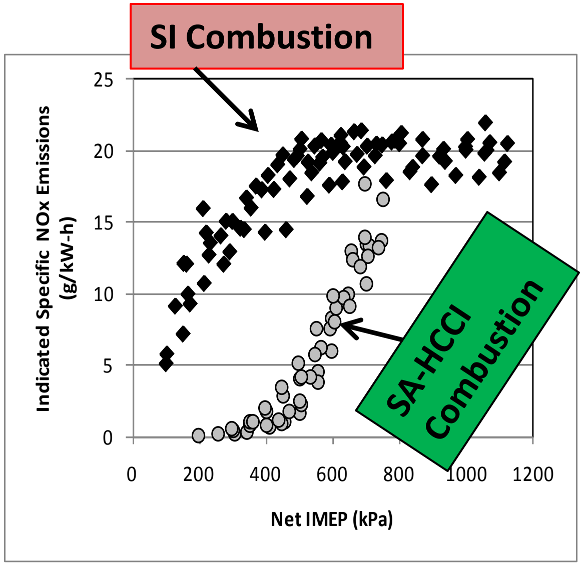


Improved combustion efficiency and NOx emissions for SA-HCCI

NOx emissions for SA-HCCI can still be substantial

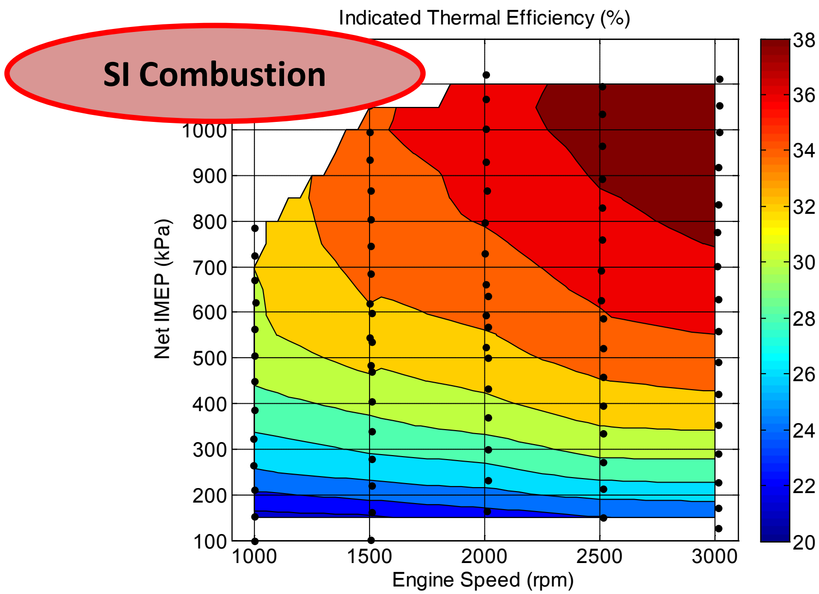


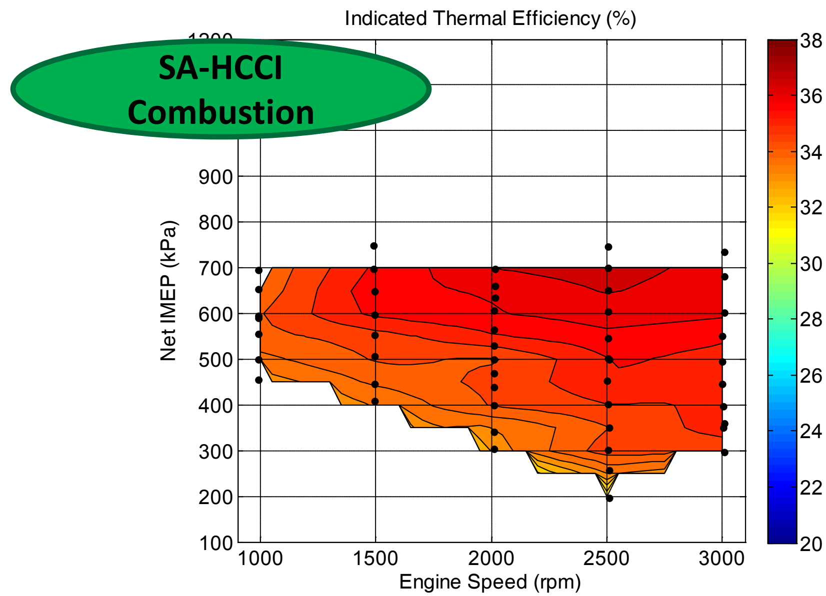




- CO and HC emissions reduced by more than a factor of 2 at most operating points, resulting in very good combustion efficiency
  - Low combustion efficiency for SI combustion can be attributed to un-optimized combustion and engine breathing differences caused by HVA valvetrain
- Near-zero NOx emissions at lowest loads, but sharp increase with increasing load
  - Due to a combination of larger fraction of SI combustion, less internal EGR, and more fuel consumed per cycle
  - Stoichiometric A/F ratio and sufficiently high exhaust temperature maintains compatibility with 3-way catalyst technology

SA-HCCI provides a substantial efficiency improvement at most operating conditions





- Efficiency benefits for SA-HCCI are greatest at low-load conditions
  - Thermal efficiency for SA-HCCI is nearly constant across entire operating range
  - Wide variations in efficiency in SI
- Increased efficiency for SA-HCCI is attributed to 3 factors
  1. Higher combustion efficiency
  2. Reduced pumping work
  3. Shorter combustion duration

Summary and conclusions

- A mode of advanced combustion has been developed and base-lined
  - Stoichiometric SA-HCCI with negative valve overlap
  - Unthrottled operation
  - Late intake valve closing angle and spark timing control pressure rise rate
- Capable of higher engine load than most advanced combustion strategies because of increased control over pressure rise rate
  - Combustion event dominated by volumetric heat release at low loads
  - Larger fraction of fuel energy burned during SI combustion at higher loads
- Improvement in CO and HC emissions compared to SI combustion
- Improvement in NOx emissions, but sufficiently high that there is a need for NOx aftertreatment
  - Stoichiometric A/F ratio maintains compatibility with conventional 3-way catalysts
- Efficiency benefit at most operating conditions
  - Efficiency benefit greatest at low load
- This study will be presented at the 2010 SAE Powertrains, Fuels and Lubricants Conference as SAE Technical Paper 2010-01-2172

Paths to SA-HCCI implementation

- **SA-HCCI combustion on cam valvetrain is the most likely route to commercial viability**
  - HVA valvetrains face numerous implementation barriers
- **2-step valvetrains have the potential to switch between conventional SI combustion and advanced combustion modes**
  - Conventional valve lifts and duration for SI combustion
  - Low lift, short duration valve events for advanced combustion
- **Valve lift and duration of the advanced combustion cams will be fixed**
  - Phase cams for desired NVO duration and intake valve closing angle
  - Fixed cam duration and lift will ultimately limit the operating range compared to HVA

Future work

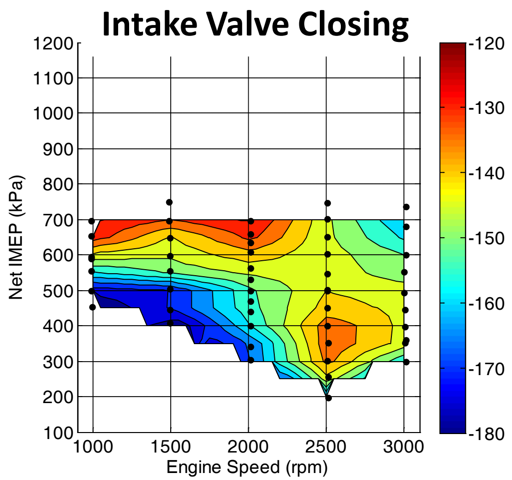
- This study is being done as part of the DOE fuels program
- A single, high octane gasoline was used in this initial study to baseline the operating strategy
- Continuing work is primarily investigating fuel effects
  - Fuels include low octane gasoline, ethanol blends (E10 and E85) and butanol blends
  - Additional investigation and refinement of the operating strategy will continue as part of fuel effects investigations

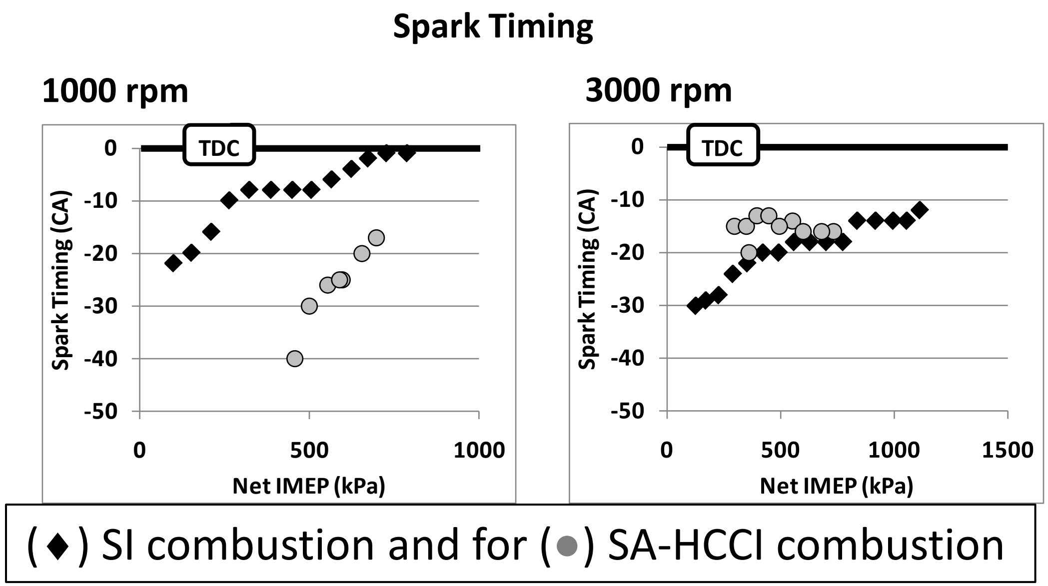
Acknowledgement

This research was supported by the US Department of Energy (DOE) Office of Vehicle Technology under the fuels technologies program with a DOE management team of Kevin Stork and Dennis Smith.

Backup Slides

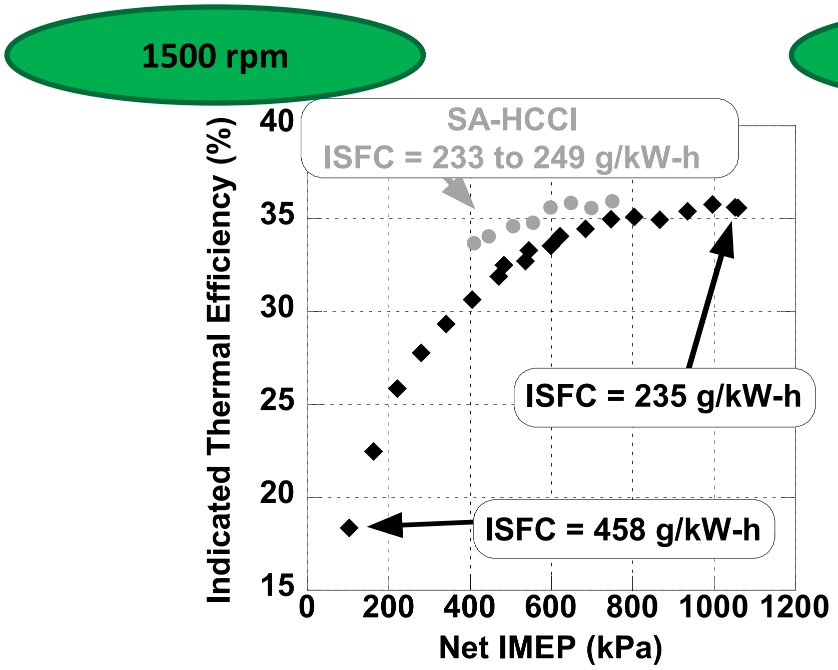
Pressure rise is effectively controlled with a combination of spark timing and intake valve closing

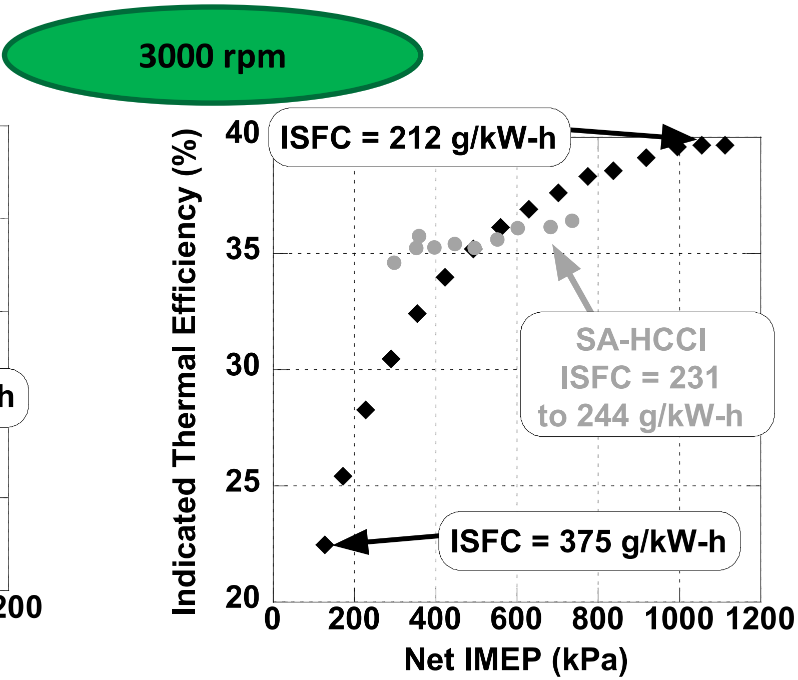




- **Retarding intake valve closing reduces effective compression ratio, retards combustion, and reduces pressure rise**
- **Retarding spark timing delays the start of combustion, retards combustion phasing, and reduces pressure rise**
- **The two control strategies are, to some extent, interchangeable**
  - **Tradeoffs between the two are a subject of an ongoing investigation**

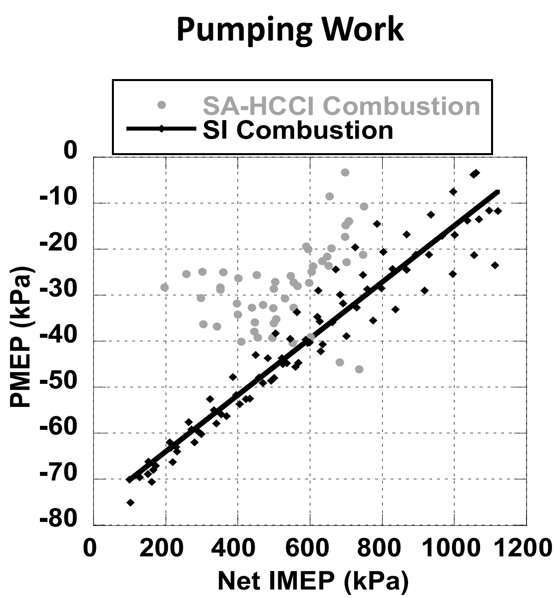
Efficiency comparison at constant engine speed

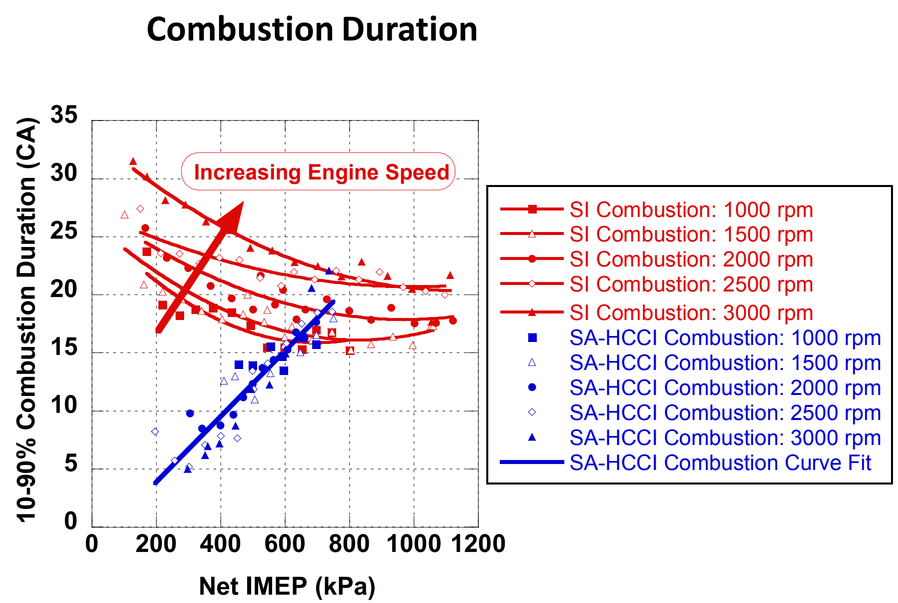




- At low engine speed, SA-HCCI provides an efficiency benefit for the entire operating range
- At high engine speed, SI combustion becomes more efficient at loads > 5 bar IMEP
- Discrepancy is due to higher efficiency for SI combustion rather than efficiency degradation for SA-HCCI

Pumping work and combustion duration differences





- Pumping work is reduced for SA-HCCI combustion strategy
  - Further reductions are likely possible with optimization of fuel injection timing and valve events
- Shorter combustion duration allows for better utilization of expansion stroke
  - Very different trends in combustion duration for SI and SA-HCCI combustion
  - SA-HCCI combustion achieves much shorter duration