High Efficiency Clean Combustion in Multi-Cylinder Light-duty Engines

Presented by Robert Wagner

Scott Curran, Vitaly Prikhodko, Kukwon Cho, Eric Nafziger, Jim Parks, Scott Sluder
Oak Ridge National Laboratory

Gurpreet Singh, Ken Howden, Drew Ronneberg
Vehicle Technologies
U.S. Department of Energy

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Overview

Activity evolves to address DOE challenges and is currently focused on milestones associated with Vehicle Technologies emissions objectives.

Timeline

- **Consistent with VT MYPP**
- **Activity scope changes to address DOE *needs***

Barriers

- **Efficiency/emissions**
- **Combustion control**
- ➡ **VT performance milestones**

Budget

- **FY 2008 $400k**
- **FY 2009 $400k**
- **FY 2010 $300k (in progress)**

Partners / Interactions

- **University of Wisconsin (dual-fuel combustion)**
- **UW-Sandia (PM modeling, common engine geometry)**
- **Delphi Automotive Systems (PFI injectors)**
- **Industry technical teams, DOE working groups, and one-on-one interactions.**
- **ORNL fuels, emissions, and health impacts activities.**

Relevance

Objective is to develop and assess the potential of advanced combustion concepts on multi-cylinder engines for highest efficiency and lowest possible emissions.

Characteristics	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Peak Brake Thermal Efficiency (HC Fuel)	41%	42%	43%	44%	45%
Part–Load Brake Thermal Efficiency (2 bar BMEP @ 1500 rpm)	27%	27%	27%	29%	31%
Emissions	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5
Thermal efficiency penalty due to emission control devices	< 2%	< 2%	< 2%	< 1%	< 1%

Addresses challenges related to implementation of high efficiency combustion concepts on multi-cylinder engines.

- **High dilution levels**
- **Heat rejection**
- **Boosting**
- **Thermal management**
- **Adaptive controls**

Milestones

- **FY 2010 Q3 – In progress (coordinated with Fuel Technologies Program)**

  Quantify efficiency/emissions potential of a dual-fuel advanced combustion approach on a multi-cylinder light-duty engine.

- **FY 2010 Q4 – In progress**

  Characterize sensitivity of advanced combustion operation to engine thermal conditions and impact on efficiency, emissions, and stability.

Approach

Modeling + Experiments + Analysis + Collaboration

- **Modeling**
  - » Combustion modeling for guiding experiments (with University of Wisconsin).
  - » Dynamic models for understanding dispersion phenomena and developing *real time* controls and feedback metrics.
  - » Engine-system models for evaluating efficiency opportunities/losses.
  - » Vehicle system models for estimating real-world fuel economy potential.
- **Experiments**
  - » Multi-cylinder to address implementation issues related to cylinder-to-cylinder balancing, dilution, heat rejection, turbo-machinery, …
- **Analysis**
  - » Thermodynamic analysis to understand fuel usage distribution.
  - » Gaseous and PM emissions analysis to understand combustion process, aftertreatment matching, and for model validation.
- **Collaboration**
  - » University of Wisconsin on dual-fuel modeling and single-cylinder experiments.
  - » Delphi Automotive Systems on PFI fuel injectors.
  - » ORNL fuels, emissions, and health impacts activities.

Engine experiments make use of two GM 1.9-L engines

- **Three controllers *in use***
  - » dSpace MABX with Ricardo VEMPS.
  - » National Instruments based system developed by Drivven.
  - » “Open” ECU supplied by GM.
- **Hardware modifications and/or additions**
  - » Expanded temperature control of coolant, lubricant, EGR, fuel.
  - » Port-Fuel-Injection (PFI) gasoline fuel system.
  - » Low pressure EGR system.
  - » BorgWarner 2-stage turbocharger system (*in progress*).
- **Instrumentation**
  - » Temperatures and pressures necessary for 2nd Law analysis.
  - » In-cylinder pressure all four cylinders.
  - » Extensive exhaust characterization and special diagnostics.
- **Advanced technology integration**
  - » Emission control devices.
  - » Waste heat recovery systems.
  - » Alternative fuel and dilution systems.

Number of Cylinders	4
Bore, mm	82.0
Stroke, mm	90.4
Compression Ratio	17.5
Rated Power, kW	110
Rated Torque, Nm	315

2-stage turbocharger (graphic used with permission of BorgWarner)

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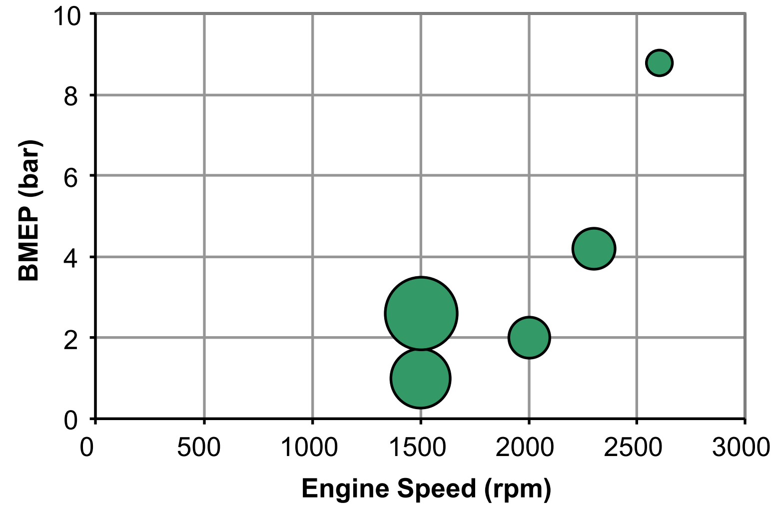
Focus on engine conditions consistent with light-duty drive cycles and with those used in related activities at ORNL and elsewhere

- **Used to estimate drive-cycle emissions and efficiency for technology comparisons.**
- **Considered representative speed-load points for light-duty diesel engines.**
- **Method does not account for cold-start, transient phenomena, aftertreatment regeneration, etc.**



Point	Speed / Load	Weight Factor	Description
1	1500 rpm / 1.0 bar	400	Catalyst transition temperature
-	1500 rpm / 2.0 bar	NA	VT milestone condition (not included in FTP estimate)
2	1500 rpm / 2.6 bar	600	Low speed cruise
3	2000 rpm / 2.0 bar	200	Low speed cruise with slight acceleration
4	2300 rpm / 4.2 bar	200	Moderate acceleration
5	2600 rpm / 8.8 bar	75	Hard acceleration

Road-load condition defined for milestones in VT MYPP

For more information on modal conditions see

SAE 1999-01-3475, 2001-01-0151, 2002-01-2884, 2006-01-3311 (ORNL)

Technical Accomplishments Summary

- **Demonstrated dual-fuel combustion concept on multi-cylinder engine.**
  - » Collaborated with University of Wisconsin to bridge modeling to multi-cylinder experiments.
  - » Characterized implementation challenges and potential for high efficiency and low emissions.
  - » Explored influence of intake mixture temperature, boost pressure, swirl, and combustion phasing.
  - » Next steps include other engine speed-load combinations, speciation of gaseous and PM emissions, and ethanol blends.

- **Explored load expansion and sensitivity of PCCI operation to thermal boundary conditions.**
  - » Load expansion of HECC operation.
  - » Low pressure / high pressure EGR balancing for maximizing BTE with lowest possible emissions.

- **Substantial modifications for better control in support of high efficiency advanced combustion research.**
  - » **High Speed Controls** – National Instruments based system with "next cycle" control capability.
  - » **Port-Fuel-Injection Gasoline System** – Added to light-duty diesel engine with integrated controller conducive to algorithm development.
  - » **Expanded Dilution** – Integrated LP EGR system.
  - » **Efficient Turbo-Machinery** – 2-Stage BorgWarner turbocharger system (in progress).
  - » **Thermal Boundary Control** – Increased temperature authority and control of intake, EGR, lubrication, and coolant systems.

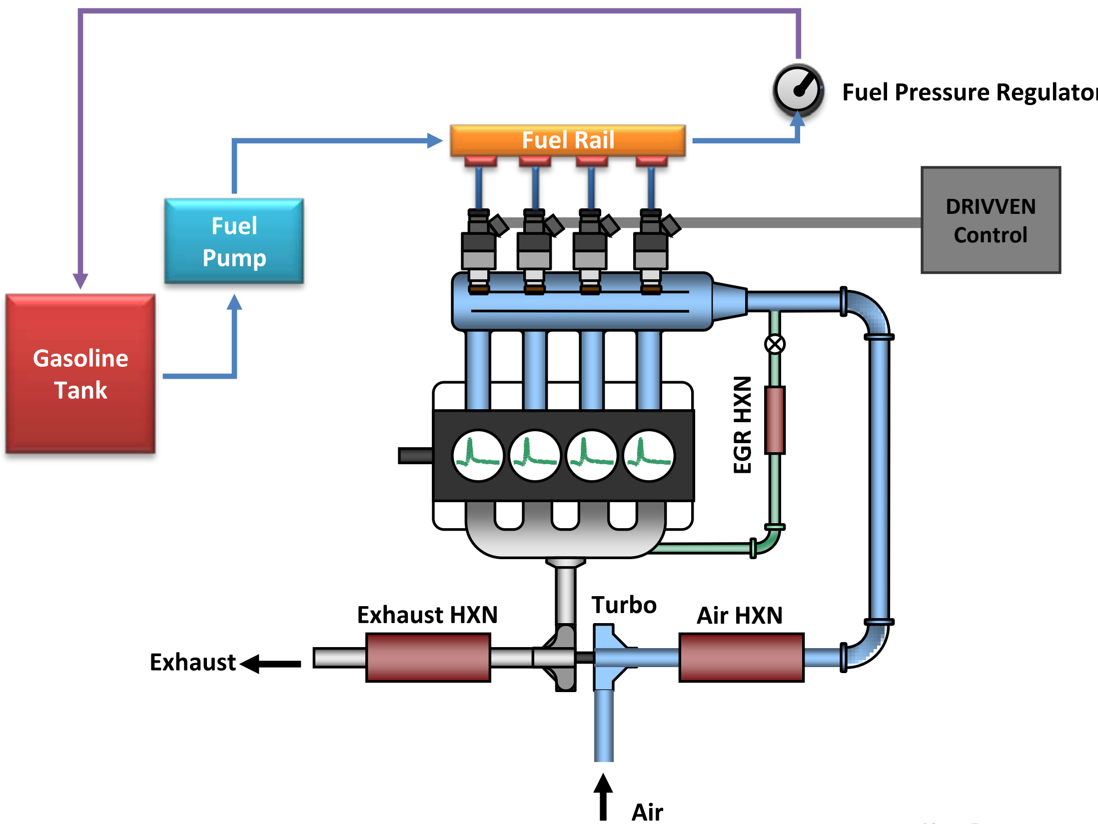
Dual-fuel operation is under investigation in collaboration with UW

- **Dual-fuel approach shown at UW to have high indicated thermal efficiency with very low emissions.**
  - Modeling ~49% Net ITE.
  - Single-cylinder experiments ~45% Net ITE.
- **Multi-cylinder implementation has additional challenges.**
- **UW support to ORNL includes:**
  - Modeling of GM 1.9-L engine to provide guidance on gasoline / diesel balancing, diesel pilot parameters, and intake charge conditioning.
  - Dual-fuel start-up procedure.

See Kokjohn et al. (SAE 2009-01-2647) and Hanson et al. (SAE 2010-01-0864) for more details on dual-fuel concept.

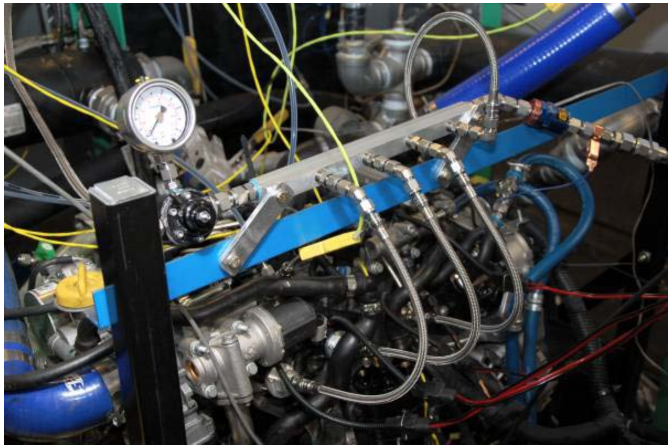
Engine modifications included addition of PFI gasoline fuel system

- **Intake charge conditions based on UW modeling within range of current hardware configuration.**
  - Port fuel gasoline injection with single in-cylinder diesel injection.
  - No EGR.
  - Intake pressure 1.3 bar.
  - Intake temperature 40 °C.
- **DRIVVEN control system.**
  - Full control of both diesel and gasoline injection timing, cylinder-to-cylinder balancing, swirl valve, variable geometry turbo, etc.
  - Standard "next-cycle" control capabilities.
  - Future experiments will make use of "next-cycle" control and adaptive nonlinear controls experience to address potential stability and balancing issues.



More details on modifications to GM 1.9-L MCE

Modified intake showing PFI injectors. Cylinder 1 is offset due to high pressure pump interference.



System installed on engine with common gasoline fuel rail.

Delphi Multec-3 extended tip injectors with narrow spray angle.

Initial experiments focused on speed-load condition consistent with LD drive-cycle modal point (2300 rpm, 4.2 bar BMEP)

Key Points

- **Approximates 2300 rpm, 4.2 bar BMEP condition.**
- **PFI gasoline.**
- **Single event diesel injection.**
- **No EGR.**

Parameter space investigated in these experiments.

Condition	Modeling (UW)	Experiment (ORNL)
Net IMEP [bar]	5.5	5.5
Speed [rev/min]	2300	2300
Total Fuel Mass [g/s]	1.16 g/s	1.22 g/s
Estimated Inj. Pressure [bar]	500	500
Percent premixed gasoline [% mass]	65 to 85	65 to 85
Diesel injection timing [° ATDC]	-20 to -60	-30 to -70
Intake Surge Tank Pressure [bar]	1.3	1.1 to 1.3
Intake Surge Tank Temperature [° C]	40	38 to 45
Swirl Level [% DC]	OEM	40 to 100 (max)
Relative Humidity (%)	14	58
Diesel Fuel	ULSD	ULSD
Gasoline (Octane (R+M)/2)	91.60	91.95

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Modeling information from University of Wisconsin provided guidance on establishing efficient dual-fuel operation

NOx limit = 1 g/kgf
PRR limit = 10 bar/°

% Gasoline	Diesel SOI [°ATDC] -20	-30	-40	-50	-60
65	184	184	182	17[illegible]	170
70	181	179	180	171	168
75	179	177	179	173	166
80	175	177	180	177	168
85	176	181	188	192	271

NOx Limit
PRR Limit

Operating range: Numbers indicated computed net ISFC

Source: Prof. Rolf Reitz, Sage Kokjohn, University of Wisconsin, personal communication 12/30/2009.

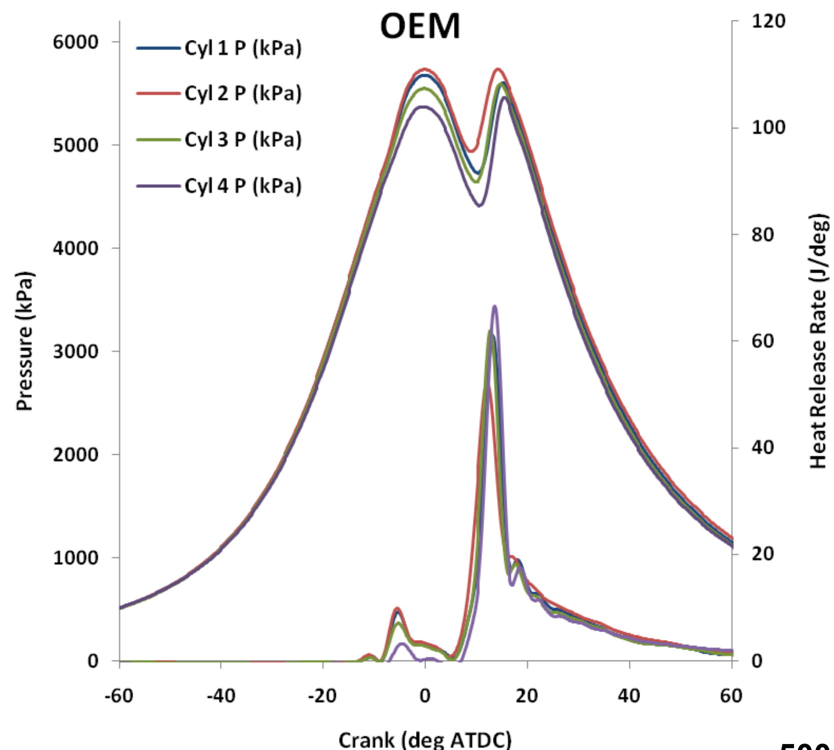
- **80 to 85% of total fuel premixed gasoline**
  - Increased gasoline percentage phases combustion later and lowers peak PRR.
- **Injection timing earlier than -30 ATDC**
- **Advancing the injection timing**
  - Lowers the diesel fuel equivalence ratio and extends the ignition delay.
  - Increases reactivity of the squish region and lowers UHC levels.

Reference condition

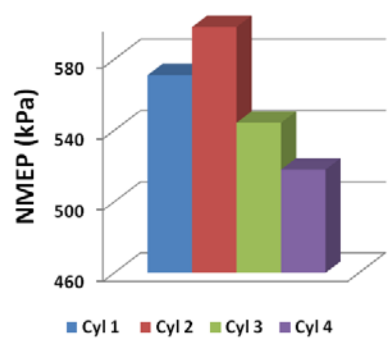
2300 rpm, 5.5 bar IMEP

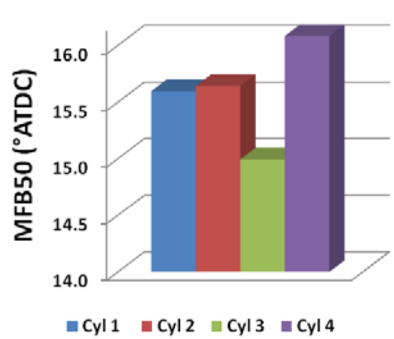
Operating Parameters	
Boost (bar)	1.18
Intake Temp (C)	90
VSA DC (%)	42.6
EGR (% Vol)	15

Performance & Emissions	
BTE (%)	32.1
ITE net (%)	39.4
NOx (ppm)	94
CO (ppm)	423
HC (ppm)	296
FSN	1.78
Exhaust T (C)	412



500 cycle average



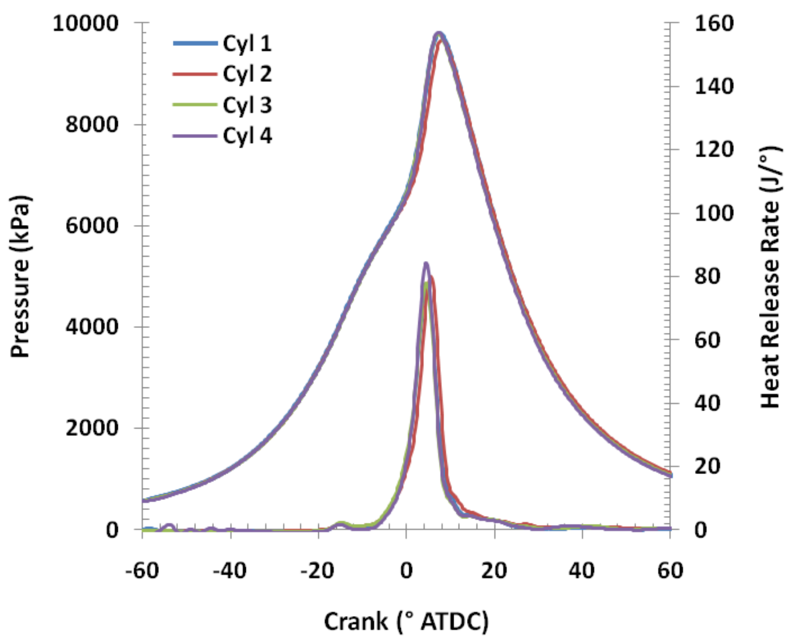


Example of dual-fuel and conventional combustion

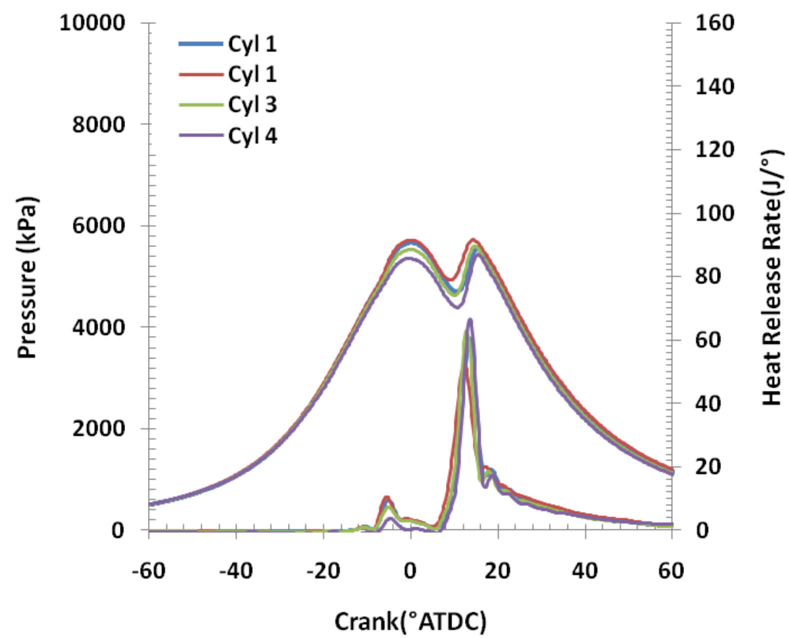
- **2300 rpm, 5.5 bar IMEP**
- **General observations as compared to conventional combustion.**

↑ BTE	↓ NOx	↓ PM	↑ CO, HC	↑ P Rise Rate	↓ Exhaust T

Gasoline/Diesel Dual-Fuel Combustion



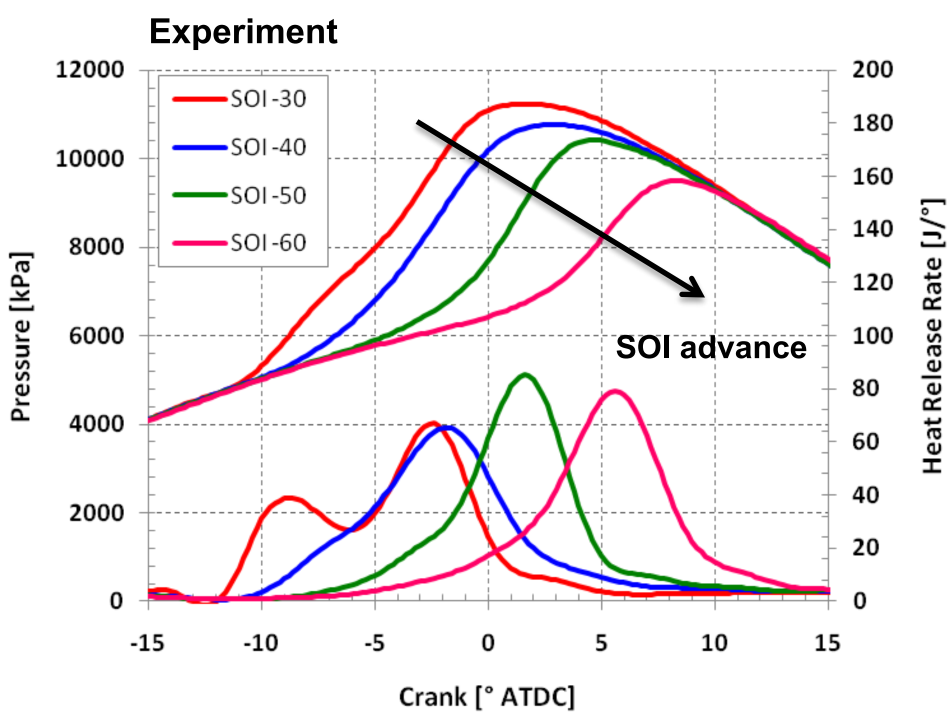
Conventional Combustion

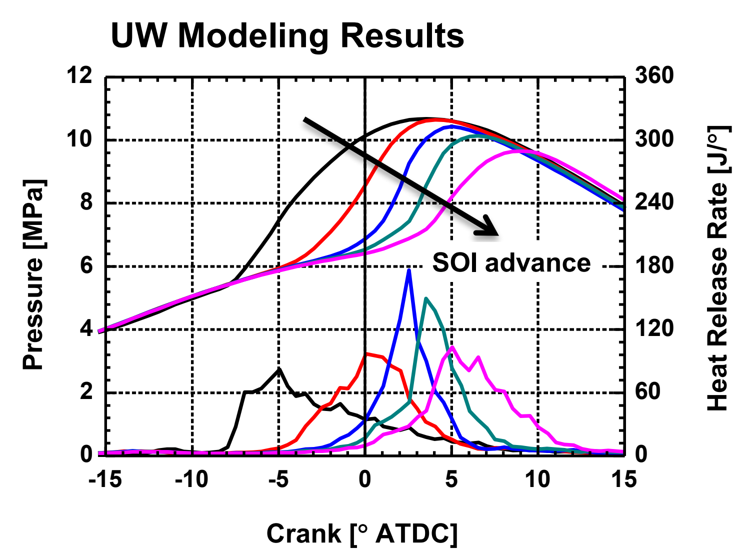


Diesel SOI used to control combustion phasing

- **Experiments trend well with modeling.**
  - » Similar agreement seen for other parameters.
- **HR double peak observed for SOI -30**
  - » Not predicted by model.
  - » Observed in single-cylinder experiments at UW.

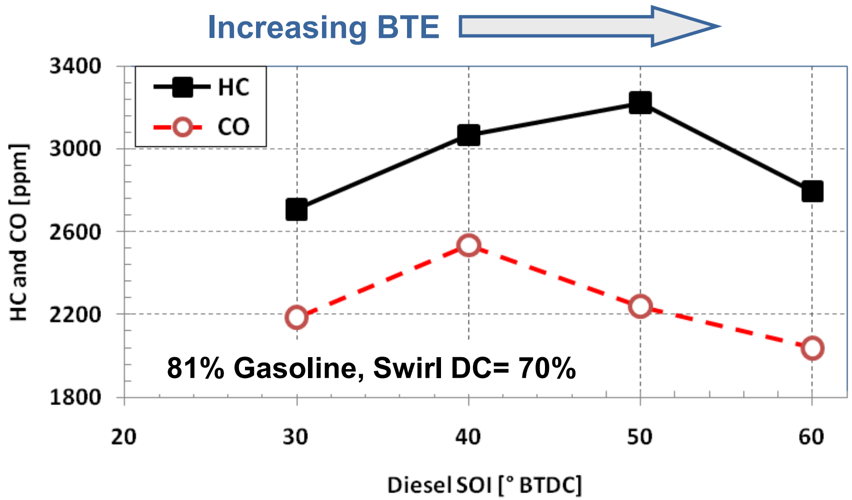
Condition	Modeling (UW)	Experiment (ORNL)
Total Fuel Mass [g/s]	1.16	1.22
Percent Gasoline (%)	80	81
Diesel SOI (° ATDC)	-20 to -60	-30 to -60
Diesel Inject P (bar)	500	500
Intake Pressure (bar)	1.3	1.3
Intake T (° C)	40	42
Swirl (DC %)	Stock	70

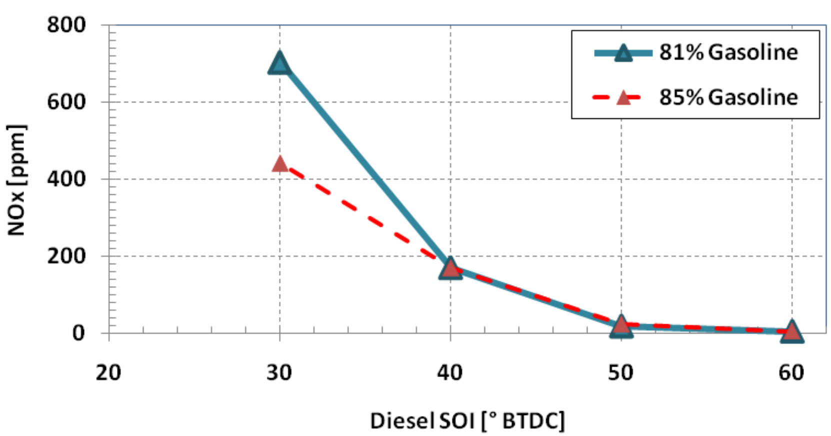


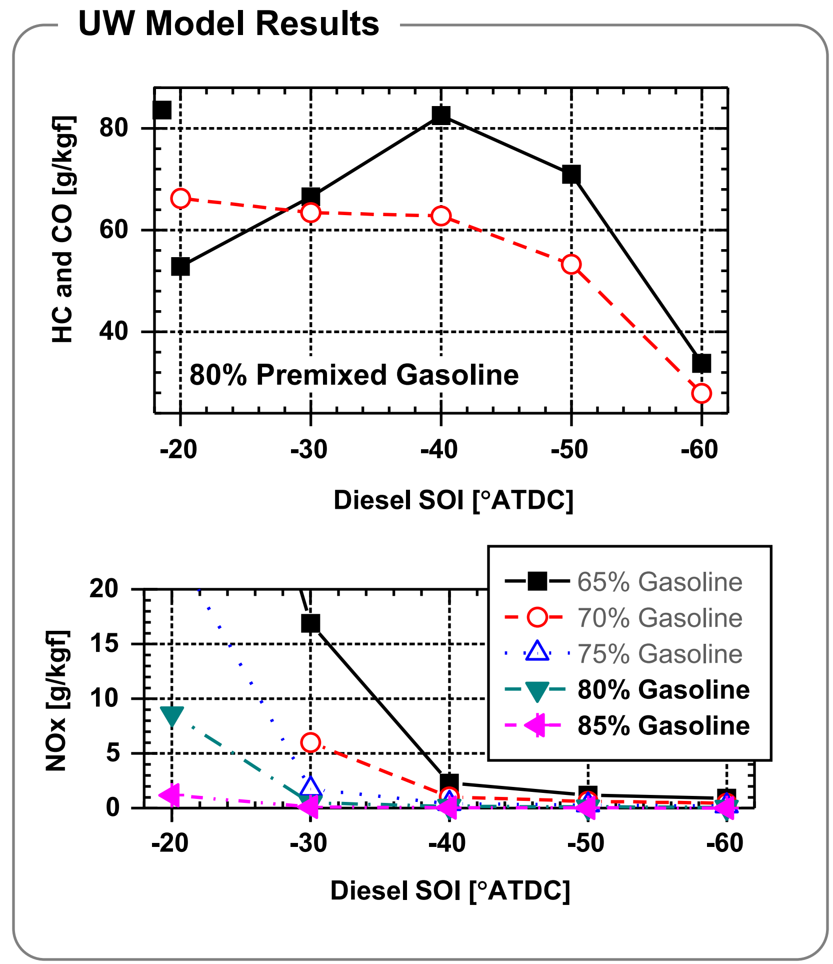


Combustion phasing effects on HC/CO and NOx emissions

- **Particulate emissions were very low for all cases.**
- **BTE is highest (32%) for SOI = 60 °BTDC.**







Overall experimental trends in ISFC similar to model predictions

- **Experimental parameter space is extensive and not fully explored or optimized.**
- **Higher ISFC (lower ITE) for experiments.**
  - » Cylinder-to-cylinder differences in inducted mass, heat rejection, etc.
  - » Cylinder-to-cylinder balancing important.

Indicated specific fuel consumption (g/kW-hr)

Experiment

% Gasoline	Diesel SOI [°ATDC] -20	-30	-40	-50	-60
65					
70					206
75					174
80		202	200	197	192
85		204	201	198	200

UW Model Results

NOx limit = 1 g/kgf
PRR limit = 10 bar/°

% Gasoline	Diesel SOI [°ATDC] -20	-30	-40	-50	-60
65	184	184	182	17[illegible]	170
70	181	179	180	171	168
75	179	177	179	173	166
80	175	177	180	177	168
85	176	181	188	192	271

NOx Limit

PRR Limit

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General Observations

- **Experimental observations mirrored model predictions.**
- **Dramatic reductions in PM and NOx with increasing BTE.**
- **Cylinder-to-cylinder balancing important for high efficiency.**
- **Swirl level has optimum level depending on gasoline-to-diesel ratio and has strong impact on BTE.**
- **Pressure rise rate sensitive to intake mixture temperature.**
- **Boost pressure also has strong impact on BTE. Higher not always better.**

Summary of "best case" results seen to date on multi-cylinder engine.

	Diesel	Dual-Fuel	
Gasoline (%)	0	81	77
Boost (bar)	1.18	1.30	1.20
Swirl DC (%)	32.1	32.2	33.6
BTE (%)	32.1	32.2	33.6
NOx (ppm)	94	5.4	7.5
FSN	1.78	0.02	0.02
CO (ppm)	423	1988	1512
HC (ppm)	296	2669	2581
Exhaust T (C)	412	247	260

Collaborations and Interactions

- **University of Wisconsin**
  - » Dual-fuel combustion modeling and sharing of experimental data and observations.
  - » PM speciation data in support of UW particulate modeling (in progress).
  - » Common engine geometry.
- **Delphi Automotive Systems**
  - » Specification and supply of several PFI injector designs.
- **General Motors**
  - » Support of GM 1.9-L engines and open controllers.
- **BorgWarner**
  - » Guidance on operation and modeling of 2-stage turbo-machinery as well as design of low-pressure EGR system.
- **Industry Tech Teams, DOE AEC/HCCI Working Groups, and one-on-one interactions.**
  - » ORNL is member of Advanced Engine Combustion Working Group which is administered by Sandia National Laboratories.
- **Other ORNL-DOE Activities**
  - » Fuels, emissions, health impacts, and vehicle systems modeling projects.

Next Steps FY 2010

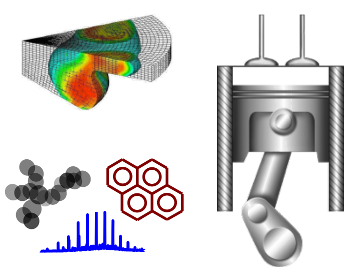
- ***On track*** **to meet milestones end of Q3 and Q4.**
- **Continue dual-fuel combustion experiments and analysis on MCE.**
  - » Thermodynamic analysis to better understand efficiency and loss mechanisms.
  - » Additional experiments at additional speed-load conditions.
  - » Refined parameter sweeps (e.g., boost, swirl, thermal boundaries, etc) to better understand efficiency-emissions trade-offs.
  - » Automated cylinder balancing with multiple engine parameters.
  - » Integration of oxidation catalyst (leveraged activity).
  - » Detailed gaseous and PM emissions characterization including speciation (leveraged activity). Information will be shared with UW for model validation.
- **Complete cell modifications to enable improved control of intake mixture composition, temperature, and pressure.**

Advanced combustion focused GM 1.9-L engine

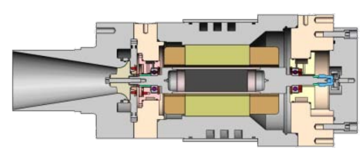
BorgWarner R2S for GM 1.9-L engine

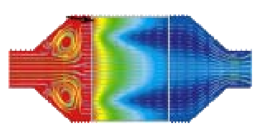
Future FY 2011

- **Continue role to develop and assess potential of high efficiency concepts on multi-cylinder engines.**
  - » Numerous concepts showing high efficiency potential in idealized single-cylinder engine.
  - » Multi-cylinder engine has additional challenges which must be addressed.
  - » Controls for improved robustness.
- **Leverage with fundamental expertise and on-going activities to better understand fuel economy potential and systems integration challenges.**
  - » Emissions characterization.
  - » Health effects issues.
  - » Aftertreatment.
  - » Fuel effects.
  - » Vehicle systems modeling and drive-cycle simulations.



Thermal Energy Recovery





Aftertreatment

Combustion / Engine → **Engine System** → **Vehicle System**

Summary

On track to meet FY 2010 milestones.

- **Relevance**
  - » Develop and assess potential of advanced combustion concepts on multi-cylinder engines for highest efficiency and lowest possible emissions.
- **Approach**
  - » Modeling + Experiments + Analysis + Collaboration
- **Technical Accomplishments**
  - » Demonstrated dual-fuel combustion concept on MCE.
  - » Explored load expansion and sensitivity of PCCI operation to thermal boundary conditions (not shown).
  - » Substantial modifications to engine-system to better support multi-cylinder combustion research.
- **Collaborations**
  - » University of Wisconsin on dual-fuel combustion.
  - » BorgWarner on 2-stage turbo-machinery and low-pressure EGR.
  - » Regular communication to DOE, industry, and others through technical meetings and one-on-one interactions.
- **Future**
  - » Continue role to explore and enable advanced concepts on multi-cylinder engines. Controls is an important component of current and future implementations.
  - » Speciation of gaseous and PM emissions in support of UW-Sandia modeling efforts.

Robert Wagner • 865-946-1239 • wagnerrm@ornl.gov