Non Petroleum Based Fuel Effects on Advanced Combustion
Project ID# FT008

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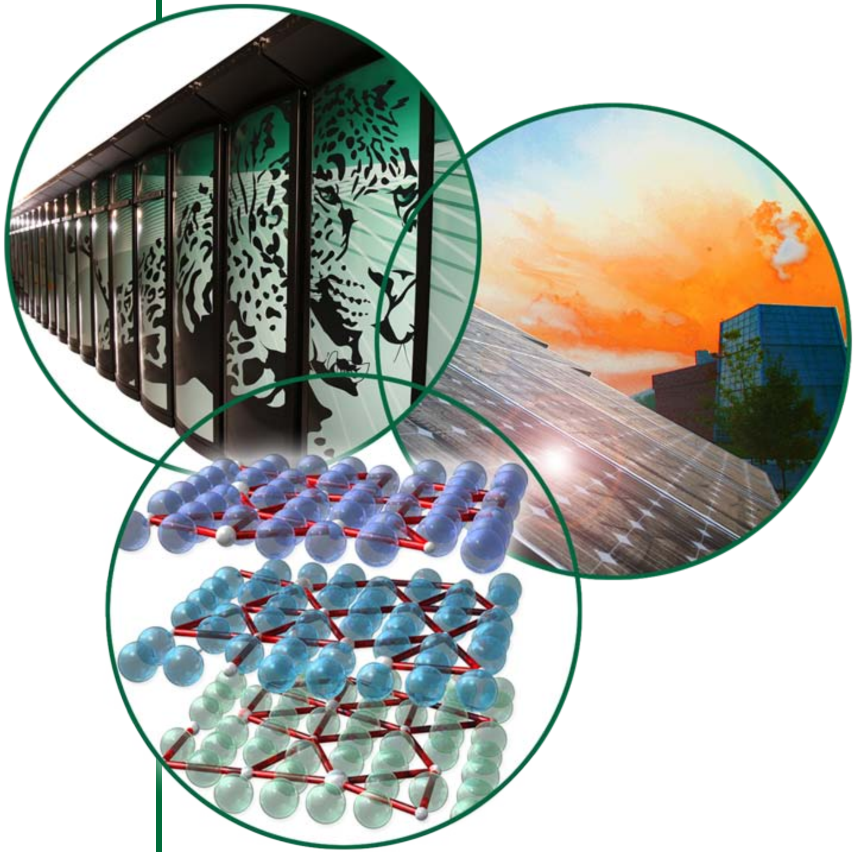

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Overview of NPBF effects on advanced combustion

Broad Barrier: Inadequate data and predictive tools to assess fuel property effects on advanced combustion, emissions, and engine optimization

- **Our role:** Determine the effects of non-petroleum based fuel properties and chemistries on combustion performance and emissions for advanced combustion regimes

Budget

- **FY09: $895k**
- **FY10: $1,470k**

Project Timeline

- **NPBF fuel effects program started at ORNL in 2004**
- **Investigations have evolved, and will to continue to evolve, with emerging research needs**

Industrial Partnerships and Collaboration

- Participation in Model Fuels Consortium, led by Reaction Design
- Members of the AEC/HCCI working group led by Sandia National Laboratory
- CRADA project with Delphi to increase efficiency of ethanol engines
- Related funds-in project with an OEM
- Related funds-in project with energy company
- Collaboration with University of Wisconsin
- Collaboration with University of Michigan

NPBF program is broad and includes numerous areas of research (1)

Multi-cylinder diesel engine platform

- Past research has focused on fuel effects of PCCI
- Current focus is on dual-fuel combustion strategy
  - Diesel with gasoline or ethanol
- University of Wisconsin collaboration
- Leveraged with APBF and HECC activity in Vehicle Technology Program (ACE016)

Milestone: Quantify efficiency and emissions potential of a dual-fuel advanced combustion approach on a multi-cylinder light-duty engine

Status: On Track (preliminary assessment complete, further analysis ongoing)

Single cylinder HCCI engine platform

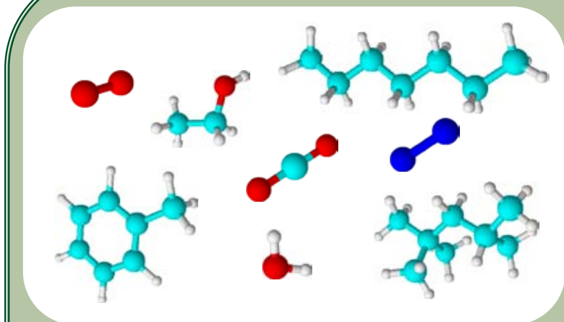
- Past research has focused on diesel and gasoline range fuel effects on HCCI combustion
- Straight-forward nature of experiment makes the engine a good platform for generating kinetic data

Milestone: Conduct experiments with surrogate fuels with different sooting tendencies ***Status: Complete***

Milestone: Investigate algae-derived and 2nd generation biofuels

Status: Working to obtain fuel samples

NPBF program is broad and includes numerous areas of research (2)



Kinetics research

- Member of the Model Fuels Consortium led by Reaction Design
- Providing experimental data for kinetics research
- Partnering with the University of Wisconsin on mechanism reduction

Milestone: Establish partnership with the University of Wisconsin for mechanism reduction. *Status: Complete*

Milestone: Develop robust multi-zone kinetic model and KIVA CFD model for Hatz HCCI engine. *Status: On Track*

Advanced Statistical Techniques

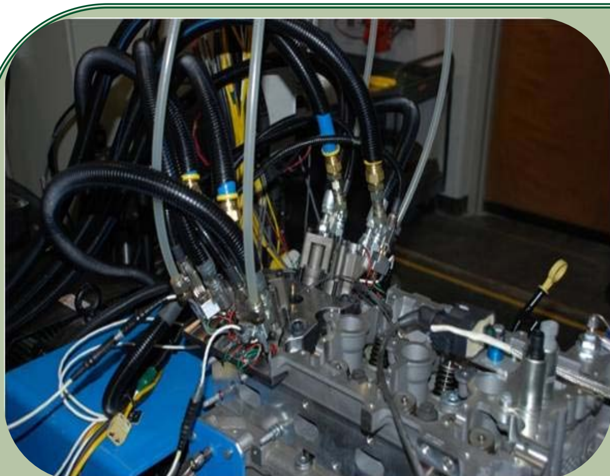
- Statistics allow for the study of complex relationships in experimental data for determination of major trends
- Project includes evaluating two different software packages and numerous statistical techniques

	AFR	BSFC	ThBT	dP/dCA	HC	CO	NOx	Smoke	LTHR	COV	FuelRate	IntakeT
AFR	1.00											
BSFC	-0.98	1.00										
ThBT	0.96	-0.88	1.00									
dP/dCA	-0.37	0.38	-0.27	1.00								
HC	-0.54	0.64	-0.59	-0.29	1.00							
CO	0.00	0.21	-0.24	-0.40	0.78	1.00						
NOx	-0.13	-0.05	0.08	-0.21	-0.21	-0.53	1.00					
Smoke	-0.79	0.83	-0.87	-0.08	0.90	0.47	0.06	1.00				
LTHR	-0.50	0.70	-0.54	0.49	0.40	0.42	-0.42	0.45	1.00			
COV	-0.74	0.69	-0.73	-0.01	0.77	0.29	0.05	0.83	0.07	1.00		
FuelRate	-0.98	1.00	-0.89	0.32	0.54	0.21	-0.06	0.82	0.70	0.68	1.00	
IntakeT	0.64	-0.82	0.72	-0.31	-0.54	-0.44	0.33	-0.01	-0.87	-0.35	-0.82	1.00

	AFR	BSFC	ThBT	dP/dCA	HC	CO	NOx	Smoke	LTHR	COV	FuelRate	IntakeT
BioPct	-0.66	0.64	-0.65	0.19	0.47	0.15	-0.17	0.49	0.33	0.54	0.64	-0.42
OxyPct	-0.31	0.31	-0.31	0.17	0.15	0.10	-0.29	0.09	0.26	0.11	0.31	-0.29
Iodine	-0.10	0.10	-0.09	0.12	0.20	-0.01	-0.07	0.10	-0.22	0.54	0.09	0.26
Cetane	-0.83	0.87	-0.89	0.23	0.55	0.13	0.39	0.79	0.86	0.50	0.87	-0.79
T10	-0.50	0.47	-0.50	-0.42	0.84	0.15	0.45	0.72	-0.15	0.93	0.45	-0.05
T50	-0.87	0.83	-0.85	0.29	0.88	0.17	-0.03	0.82	0.29	0.94	0.83	-0.43
T90	-0.51	0.50	-0.49	0.69	0.36	0.11	-0.42	0.36	0.12	0.79	0.49	-0.17

Milestone: Apply advanced statistical techniques to fuel and engine data. *Status: On Track*

NPBF program is broad and includes numerous areas of research (3)



Single cylinder GDI engine with VVA

- Operational at ORNL in FY09
- Flexible research platform for multiple investigations
    - Ethanol optimization CRADA with Delphi
    - Gasoline range fuel effects on NVO and exhaust re-breathing HCCI
    - Spark-assisted HCCI combustion

Milestone: Complete parametric experiments for optimal performance of ethanol blends using

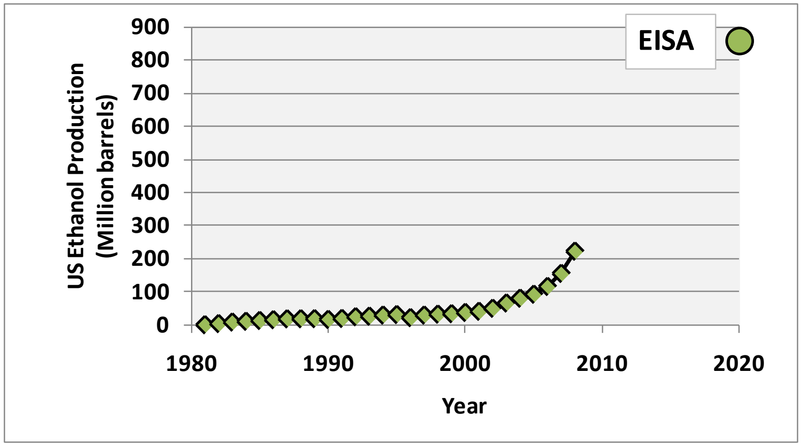
a) Single cylinder VVA engine ***Status: Complete***

b) Multi-cylinder cam VVA engine ***Status: On Track***

Reviewer feedback from 2009 merit review: ***additional focus on gasoline and ethanol is recommended***.

⇨ Experimental results will focus on ethanol optimization study

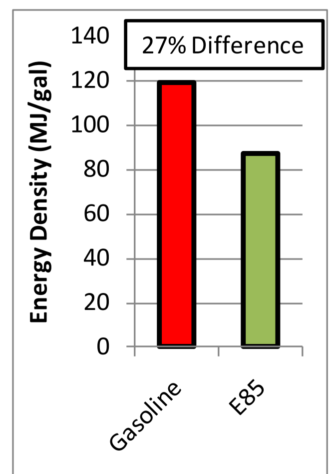
Relevance: EISA legislation requires increased use of renewable fuels, but reduced fuel economy is a market barrier for E85

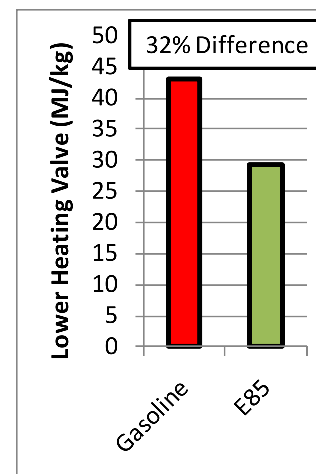


- Ethanol is primary renewable contributor for EISA targets
- Currently 99% of fuel ethanol is sold as E10, more E85 needed to comply with legislation
    - E10 alone not sufficient concentration for EISA targets
- Consumers experience 25-30% drop in fuel economy with FFV's, attributable to lower energy content

Objective: Reduce fuel economy gap between E85 and gasoline.

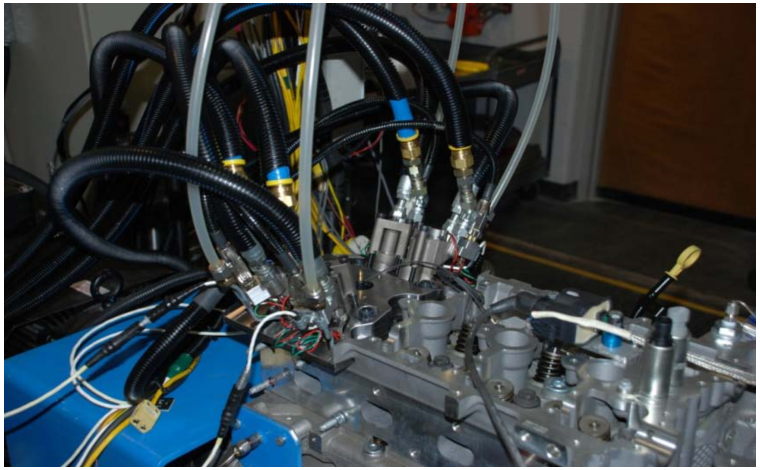
- Increase thermal efficiency of E85 by taking advantaged of advantageous fuel properties while not decreasing efficiency with gasoline.
    - Fuel properties: high octane number and high latent heat of vaporization
    - Engine technologies: high compression ratio, direct fuel injection





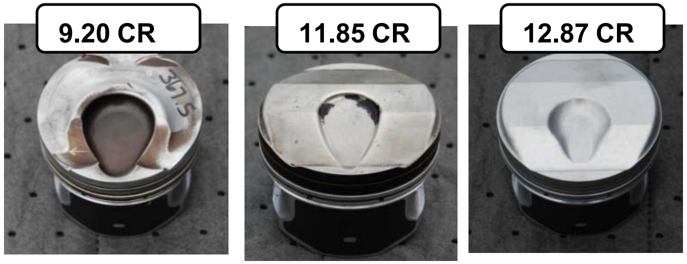
Engine approach: Single cylinder research engine with Sturman hydraulic valve actuation (HVA)

- **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**
- **Engine platform is being used for a number of additional DOE projects**
  - HCCI fuel effects on advanced combustion (APBF and NPBF)
  - SA-HCCI (APBF and NPBF)
  - Stretch efficiency
  - Delphi HCCI CRADA



Bore	86 mm
Stroke	86 mm
Connection Rod	145.5 mm
Fueling	Direct Injection
Compression Ratio	9.2*, 11.85, and 12.87
Valves per Cylinder	4

*Compression ratio with the production piston



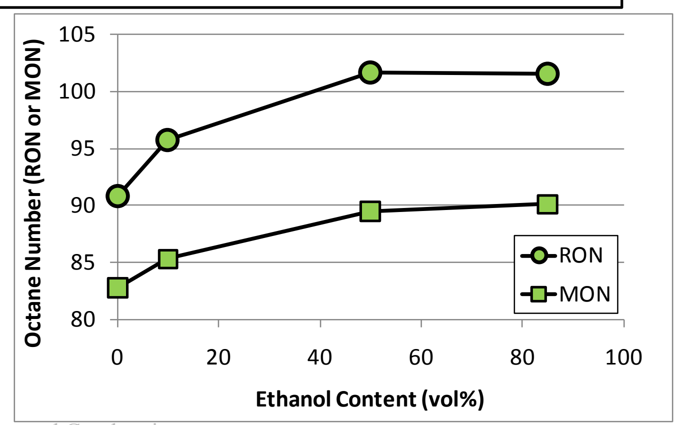
Fuel Approach: Low and high octane gasoline, three ethanol blends

Ethanol blended with RG rather than HO to better match real-world trends

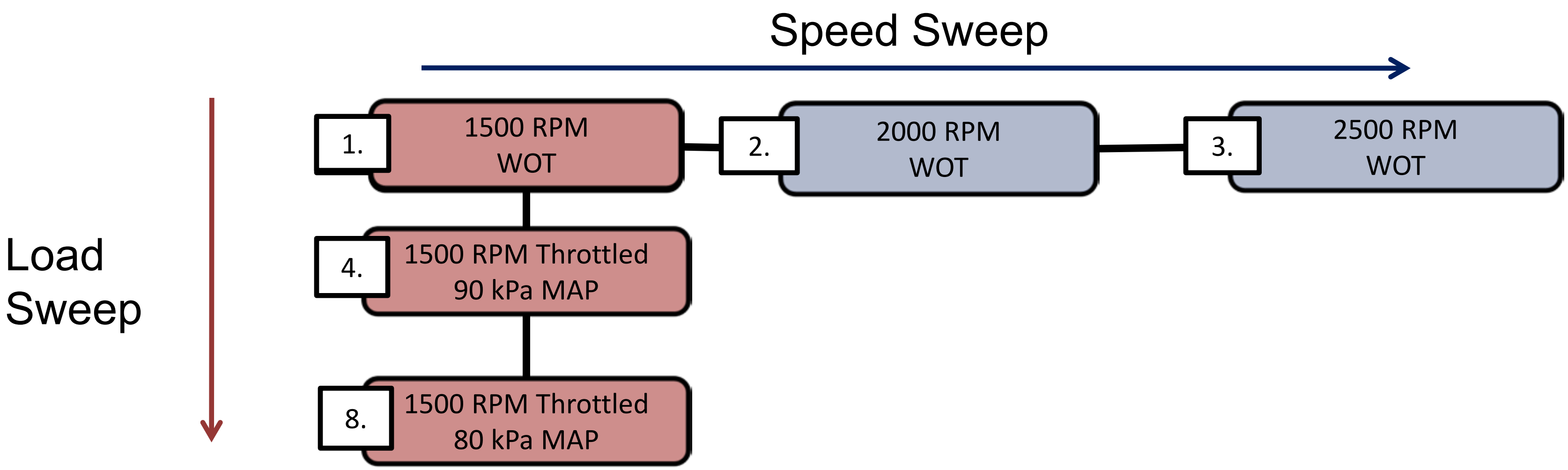
Fuel Property	Test Method	RG	HO	E10	E50	E85
Research Octane Number (RON)	ASTM D2699	90.8	96.1	95.7	101.6	101.5
Motor Octane Number (MON)	ASTM D2700	82.8	87	85.3	89.5	90.1
Antiknock Index (R+M)/2	N/A	86.8	91.6	90.5	95.6	95.8
Wt. % C	ASTM D240	86.3	86.5	81.98	68.58	56.71
Wt. % H	ASTM D240	13.7	13.5	13.28	13.19	12.97
Wt. % O	ASTM D240 by difference	0	0	4.74	18.23	30.32
Stoichiometric Air-Fuel Ratio	N/A	14.56	14.55	13.71	11.57	9.61
Specific Gravity	ASTM D 4052	0.7305	0.7400	0.7456	0.8	0.7855
Lower Heating Value (MJ/kg)	ASTM D240	43	42.8	41.5	34.8	29.2
Reid Vapor Pressure (psia)	ASTM D5191	9	9	9.9	8.3	5.6
Ethanol Content (vol%)	ASTM D5599	n/a	n/a	11.2	51.3	87.2

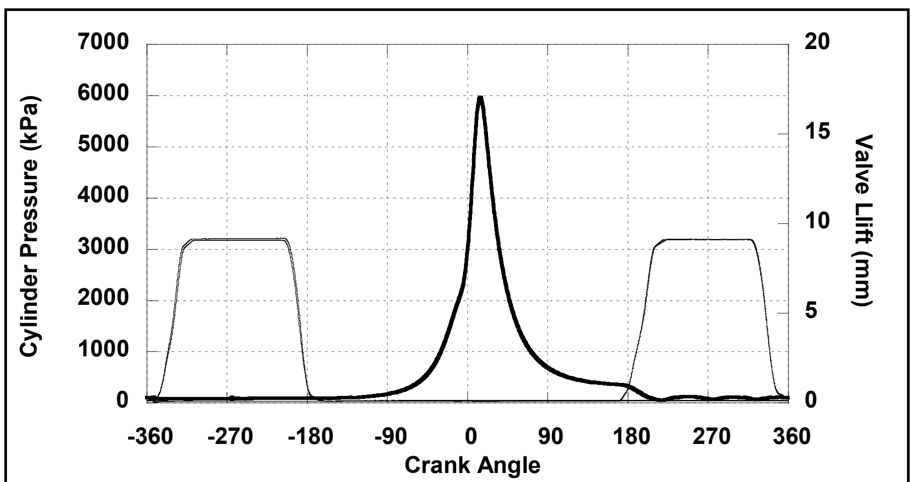
RG stands for Regular Gasoline (UTG-91 certification gasoline from CPchem)
HO stands for High Octane Gasoline (UTG-96 certification gasoline from CPchem)

Non-linear blend response to ethanol content
•Entire octane benefit realized by 50% ethanol blend



Approach 3: Engine operating conditions
Stoichiometric conditions for all points





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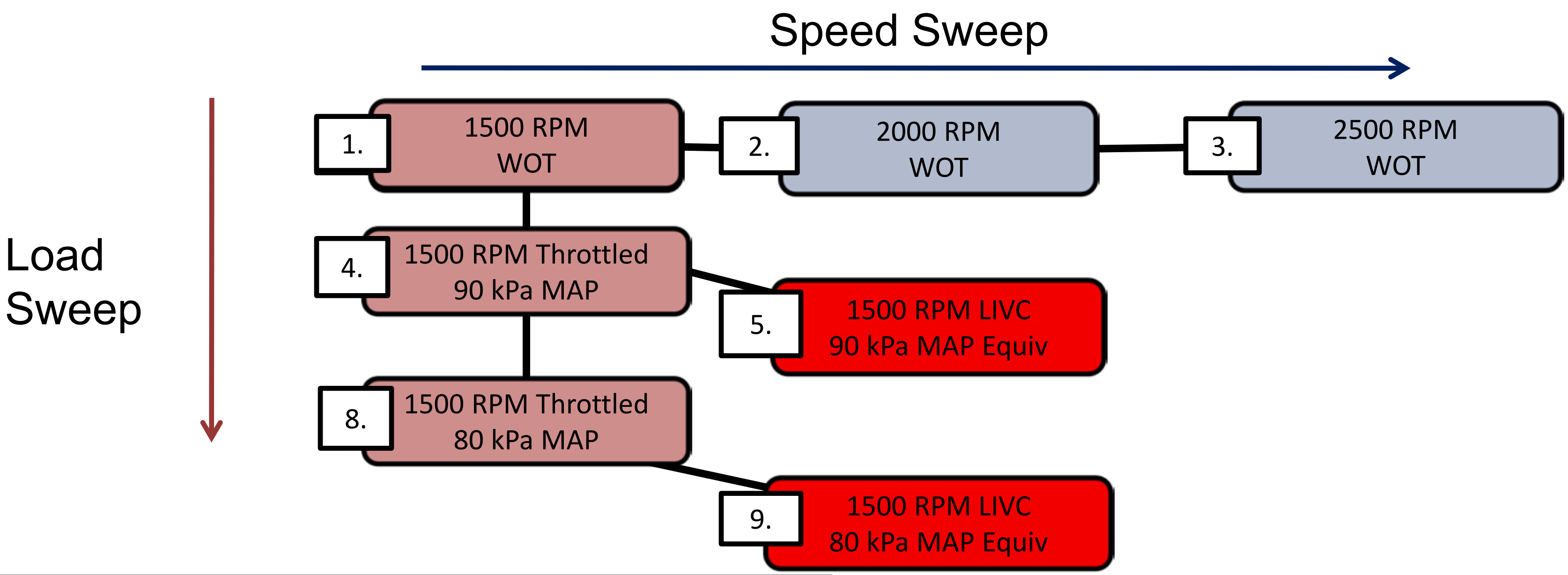

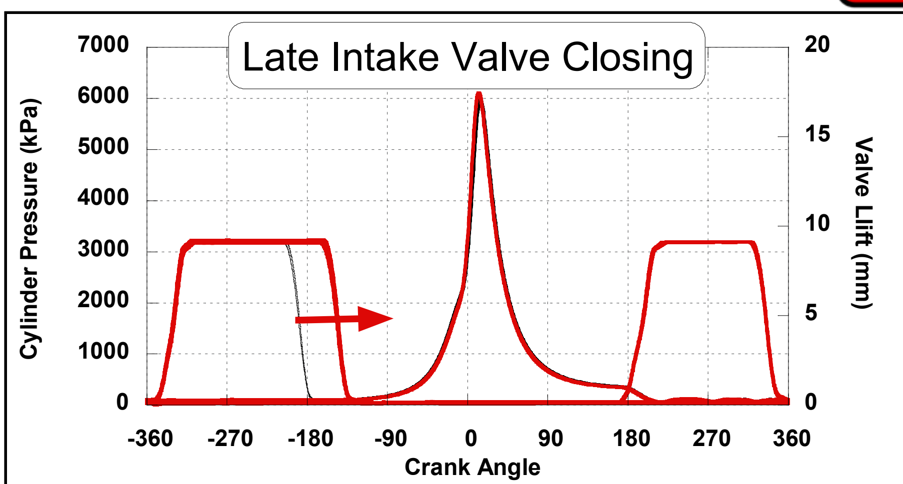

“Equivalent” conditions are based on equivalent air flow to the throttled condition

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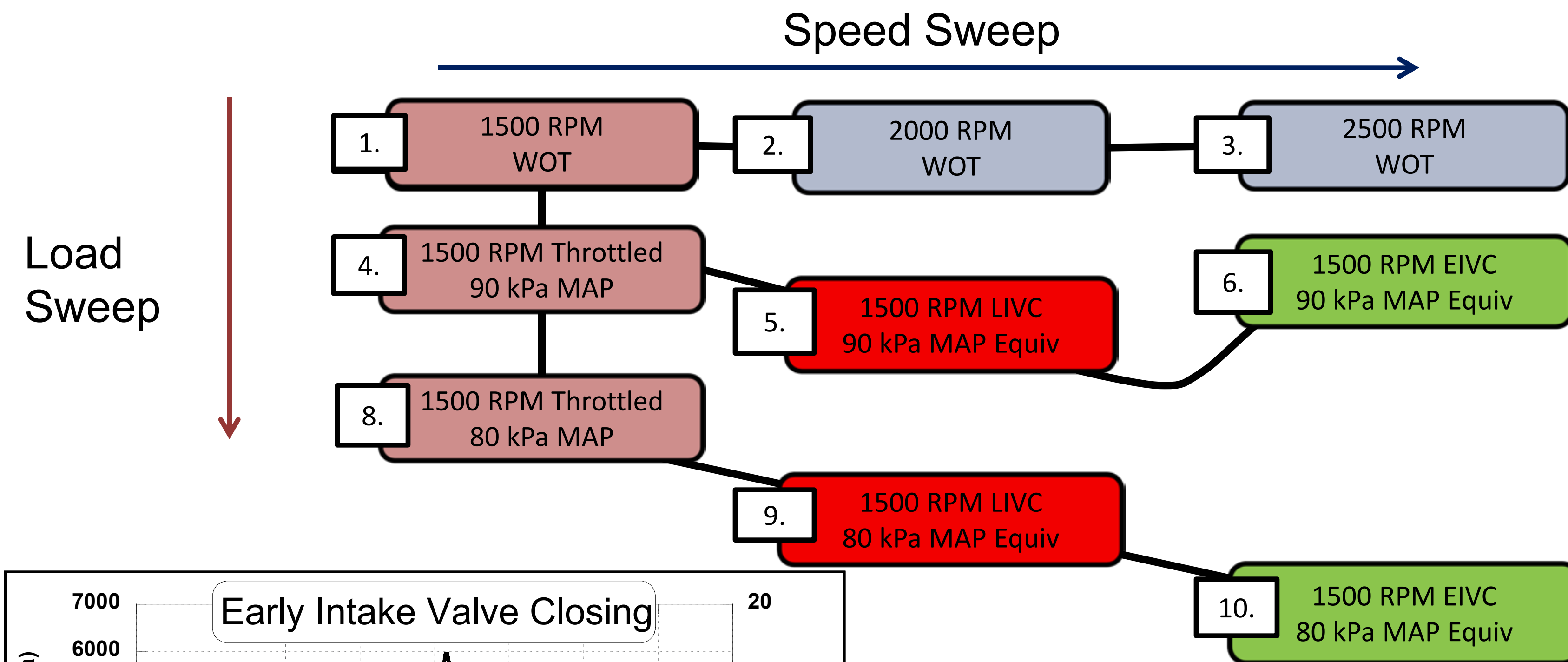

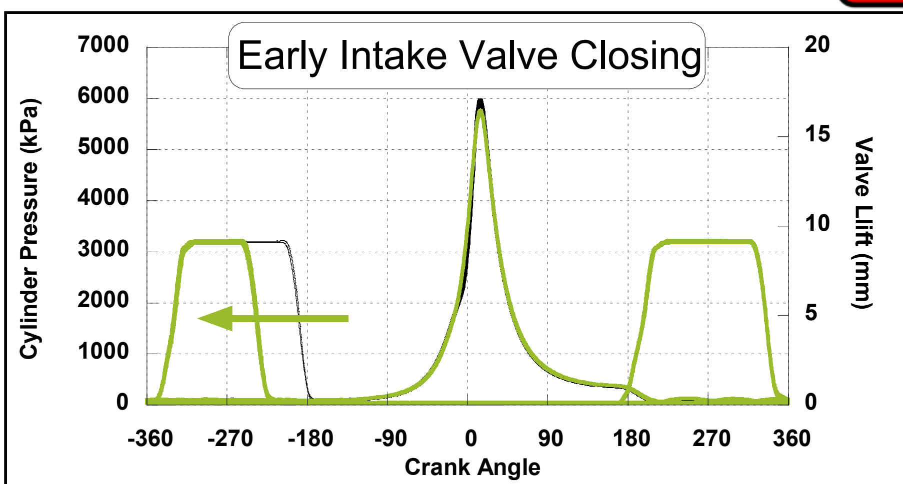

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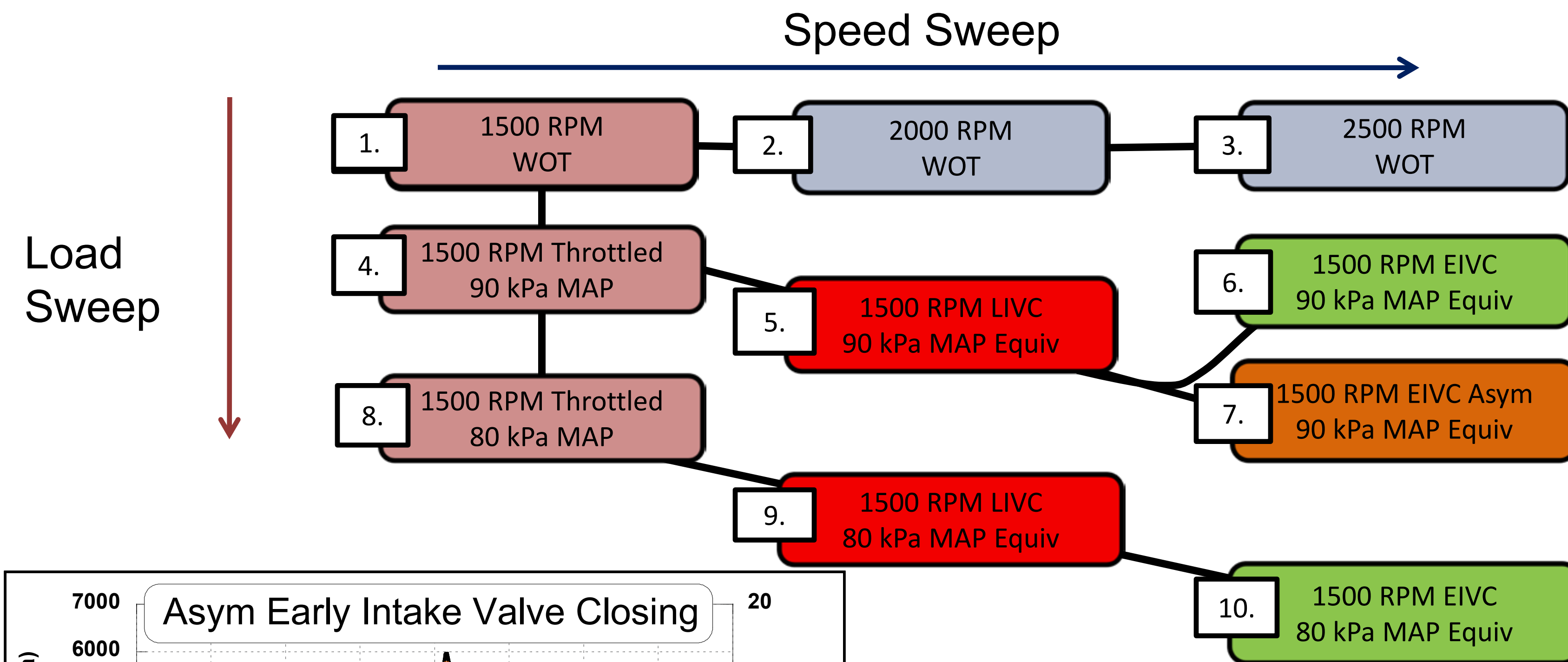
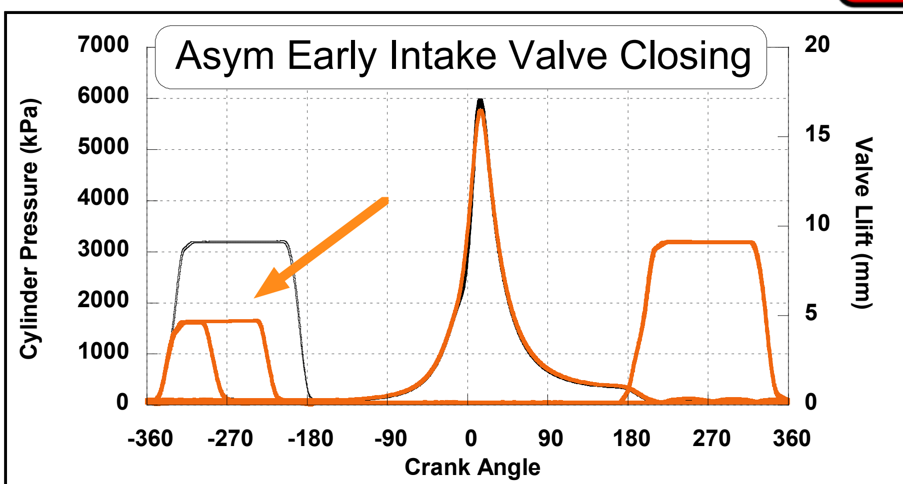
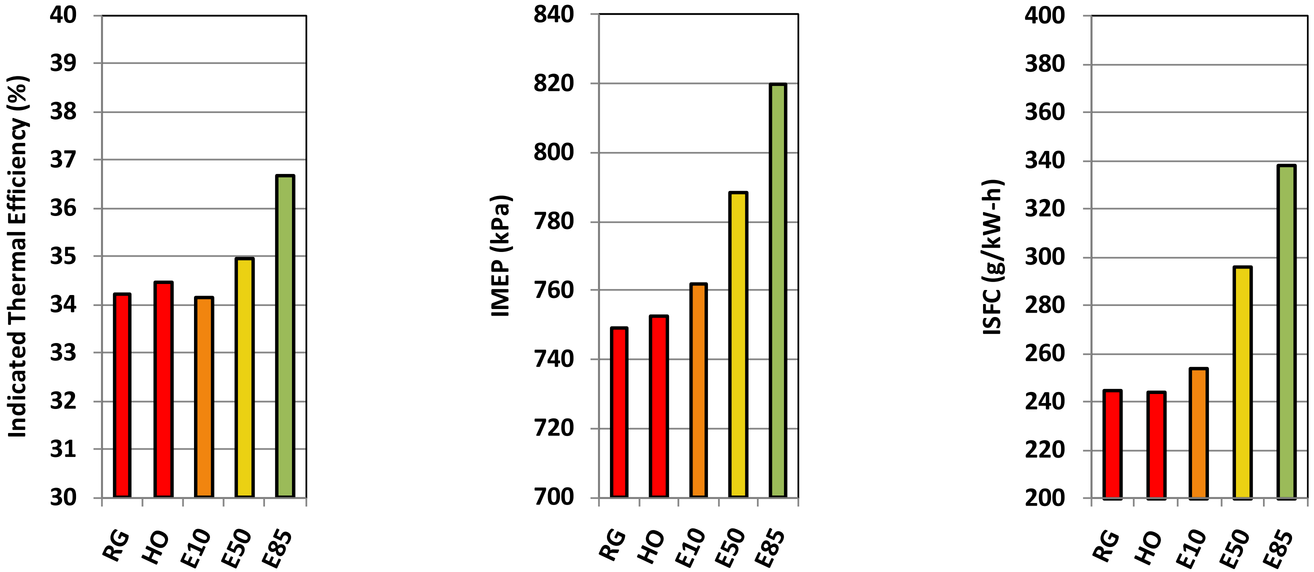




"Equivalent" conditions are based on equivalent air flow to the throttled condition

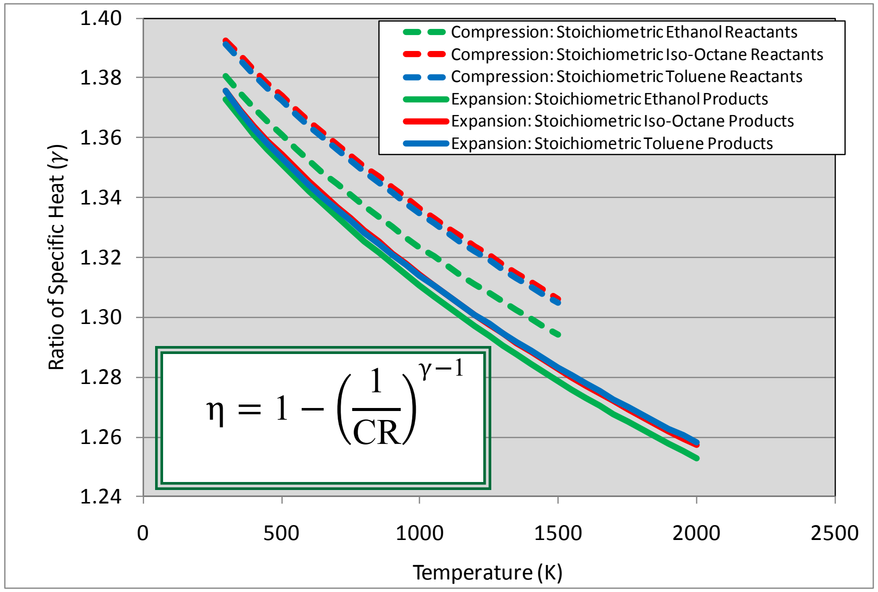
Ethanol content simultaneously increases thermal efficiency and power under conditions that are not knock-limited

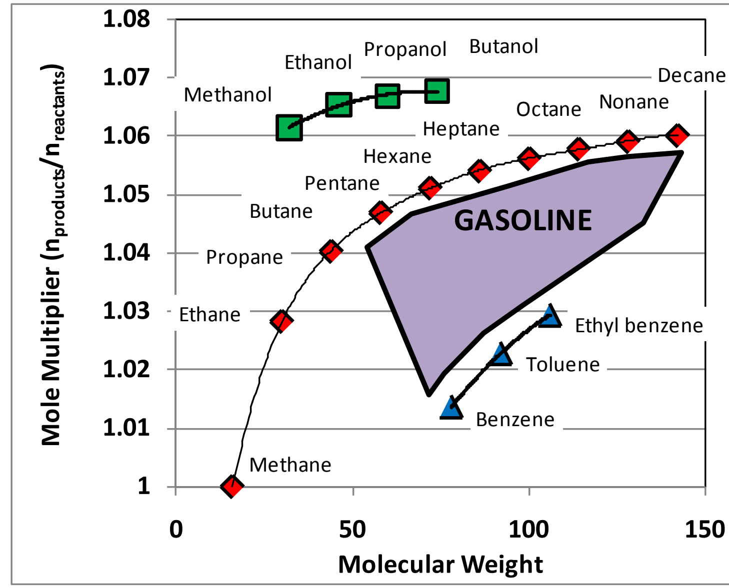


80 kPa throttled, 9.2 compression ratio, spark advance is not knock-limited for any of the fuels

- **Efficiency and power trends with ethanol have been reported previously, but root cause not fully understood**
  - **Analysis shows that about half of the power increase can be attributed to increased energy flux, due to charge cooling and higher energy content per unit mass air**
  - **Inherent thermodynamic differences between ethanol and gasoline can be used to gain insight**

Thermodynamic differences between ethanol and hydrocarbon fuels examined to determine root cause of efficiency increase



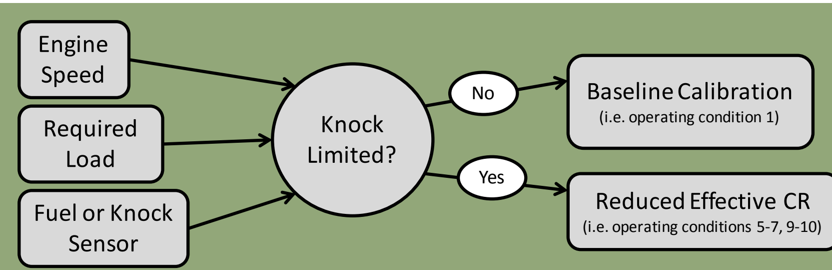


- **Lower gamma during compression with ethanol fuels serves to decrease efficiency**
- **Mole multiplier term identified and defined, MM = (moles products / moles reactants)**
  - **Alcohol fuels have higher MM than hydrocarbons**
  - **MM relates directly to relationship between LHV and exergy, and is subject of ongoing study**
- **Net effect and relative contribution of these thermodynamic effects are not yet fully understood**

Gasoline and low level blends of ethanol are knock-prone at high compression ratio

Valve strategies can be used to maintain compatibility

Sensor input can be used to determine if the operating condition is knock-limited



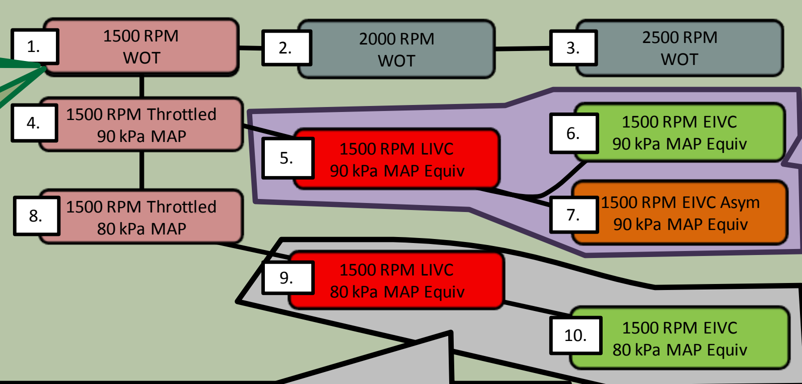
Example: Maximum power demanded at 1500 rpm with 12.87 CR configuration

E50 and E85

- Not knock-limited
- Maximum power

High Octane Gasoline

- Knock-limited, spark retard required to mitigate knock
- Small power penalty
- Substantial efficiency penalty



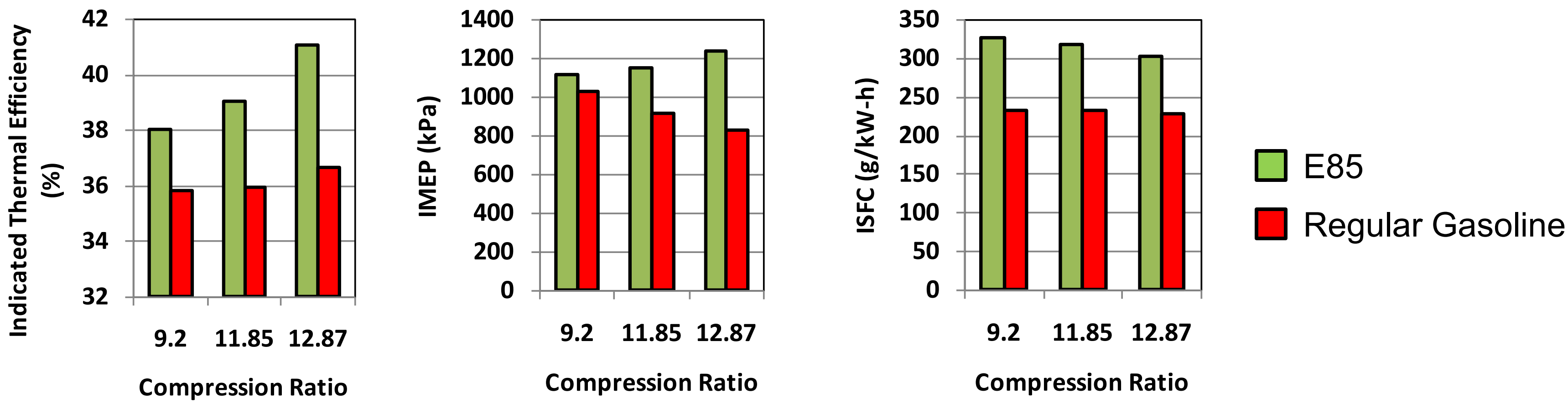
E10

- Knock-prone, EIVC to mitigate knock
- Substantial power penalty
- No efficiency penalty compared to lower CR

Regular Gasoline

- Knock-prone, LIVC to mitigate knock
- Large power penalty
- No efficiency penalty compared to lower CR

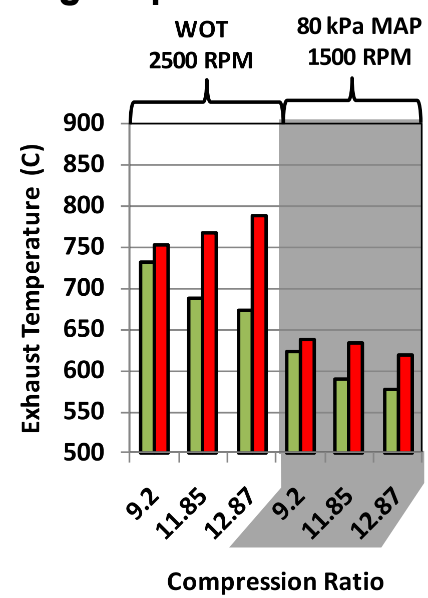
Net effect of compression ratio when maximum load is demanded at 1500 rpm



- **E85 is able to operate untrottled without knock at all compression ratios, whereas gasoline requires LIVC strategies at 11.85 and 12.87**
- **Efficiency increases with CR for both fuels, much larger increase with E85**
- **Power increases with compression ratio for E85, but decreases for**
  - **Engine power de-rated by 33% with gasoline at highest compression ratio**
- **Fuel consumption gap is reduced by 20% at the highest compression ratio**
  - **At CR = 9.2, the ISFC gap between regular gasoline and E85 is 93 g/kW-h**
  - **At CR = 12.87 the ISFC gap between regular gasoline and E85 is 74 g/kW-h**

Discussion

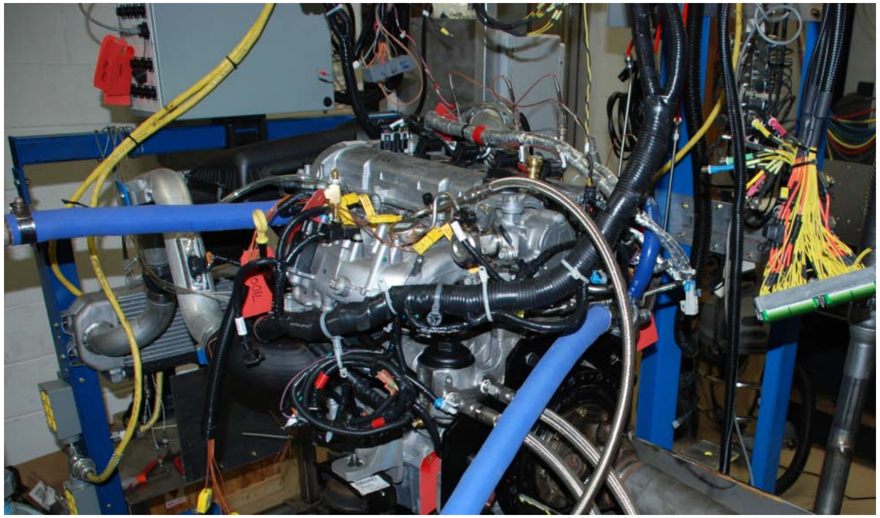
- In order to maintain compatibility with knock prone fuels, either spark retard or valve strategies must be employed
  - Spark retard has limited authority and incurs an efficiency penalty
  - EIVC and LIVC operation offer more control authority and maintain high efficiency, but can substantially de-rate the engine
- Strategies demonstrated here show that the fuel economy gap between gasoline and E85 can be reduced with no efficiency penalty for gasoline
- Results shown here are likely not representative of full engine operating map
  - Fuel economy gap may show little difference at light load conditions where gasoline is not knock-limited
  - Possible efficiency advantage for ethanol with fuel-specific engine and transmission calibration
    - Ethanol can remain in high gear where a downshift for gasoline is required to deliver demanded power
    - Lower exhaust temperature for ethanol, fuel enrichment to cool exhaust is required less frequently



Continuing FY10 ethanol optimization on multi-cylinder engine with cam-based VVA engine

Status: engine to be operational 3rd quarter FY10

- **Engine incorporates prototype 2-step variable valve actuation system, 11.85 compression ratio**
  - **Modified 2.0L GM Ecotec engine, same as single-cylinder VVA engine**
- **Capable of similar EIVC and LIVC operating strategies with production-intent valve train**
- **Drivven engine controller for flexible operation**
- **Companion engine operational at Delphi**



	Lift (mm)	Duration* (CA)	Phasing (CA)	Strategy
Intake Low Lift	5.6	131	80	EIVC
Intake High Lift	10.3	300	80	LIVC
Exhaust	10.3	240	50	--

*Valve opening and closing defined as 0.015”

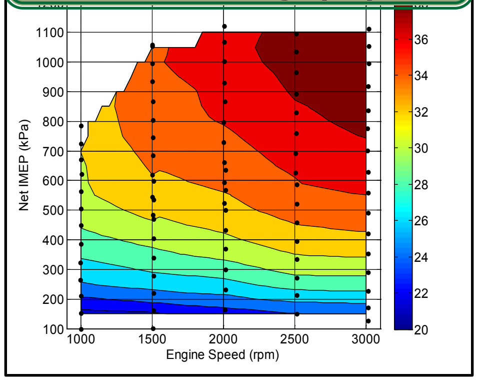
Collaborations

- Highlighted data is from a CRADA project with Delphi
- Additional collaborations
  - Member of the Model Fuels Consortium
    - Membership through CRADA, supplying experimental data for modelers
  - Member of the AEC working group led by Sandia
  - Related funds-in project with an OEM
  - Related funds-in project with an energy company
  - Collaboration with the University of Wisconsin on dual-fuel combustion mode
  - Modeling collaboration with University of Michigan

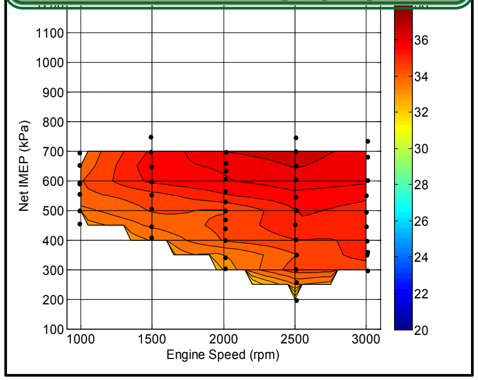
Future work

- Ethanol CRADA concluding in FY10
- SA-HCCI strategy has been developed with VVA engine for ethanol/butanol study
  - Stoichiometric operation
  - Up to 7.5 bar IMEP load
  - Substantial efficiency increase
- Multi-cylinder HECC work to continue to investigate dual-fuel strategy
  - Promising path to high efficiency with low emissions
  - Use of ethanol in diesel engines
- Continued work planned in statistical analysis and kinetics research

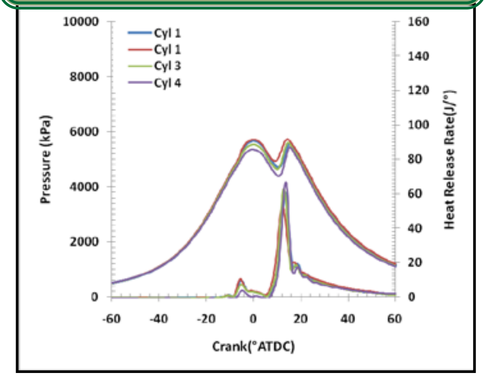
SI Thermal Efficiency (%)



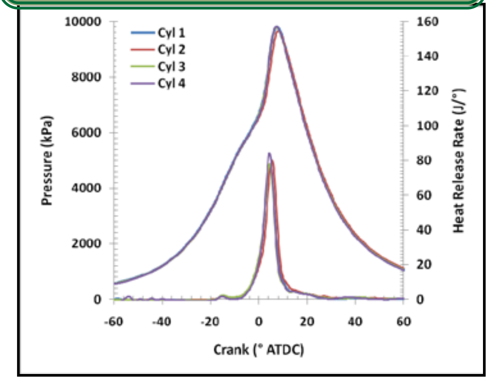
SA-HCCIThermal Efficiency (%)



Conventional Combustion



Gasoline/Diesel Dual Fuel Combustion



Summary

- There are a large number of ongoing research activities at ORNL as part of the NPBF program
  - Focused on ethanol-related activity to highlight work
  - Unable to give a full overview of all research activities in the time allotted
- Ethanol optimization investigation demonstrated ability to reduce fuel consumption gap between ethanol and gasoline
  - Ethanol is inherently more efficient than gasoline at substantially similar conditions
    - Efficiency increase is linked to thermodynamic differences of gamma and mole multiplier
    - Full understanding of this relationship is the subject of an ongoing investigation
  - Early and late intake valve closure can be used to de-rate high compression ratio engine to prevent knock and maintain compatibility with gasoline fuels
    - Demonstrated that the fuel economy gap can be reduced
      - ISFC gap reduced from 93 g/kW-h at low CR to 74 g/kW-h at high CR
    - Thermal efficiency of gasoline was actually increased under these conditions, but power reduced
    - Combustion strategies to be repeated and expanded on multi-cylinder cam-based engine
- Future work includes stoichiometric spark-assisted HCCI combustion mode with high load capabilities (up to 7.5 bar IMEP)