Development and Demonstration of a Prototype Omnivorous Engine

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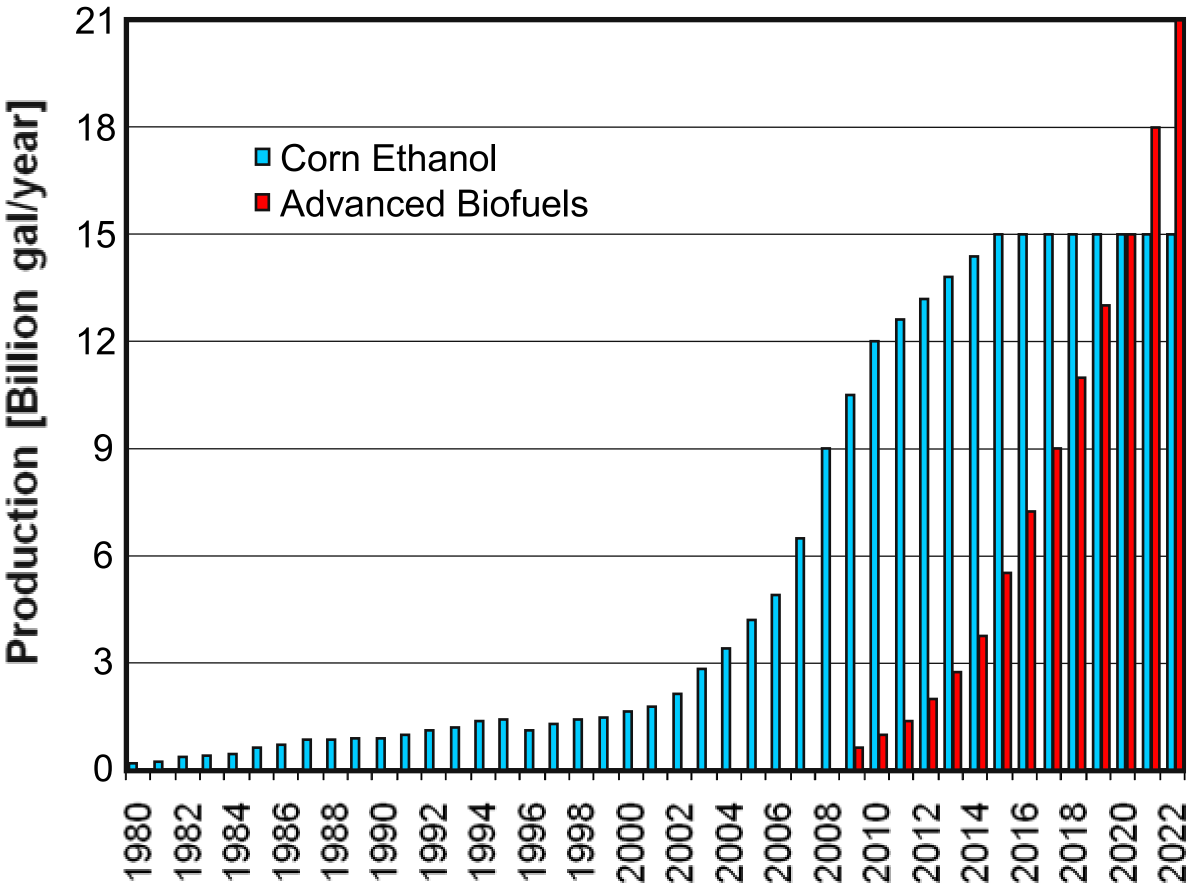
Motivation
Enable Efficient Use of Alcohol Based Fuels

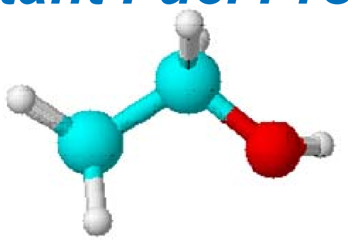


- U.S. Renewable Fuel Standard requires and increase of ethanol and advance biofuels to 36 billion gallons by 2022.
- Advanced Biofuels are fuels not made from corn (Cellulosic).

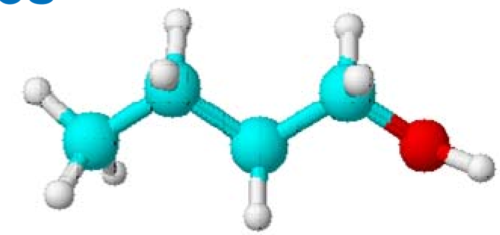
Purpose for Work

- The Omnivorous engine is a research project designed to understand flex fuel combustion and optimize a single engine to run on many different fuels with optimum efficiency.
- This work is a benchmark and is designed as a "what if" of how a modern SIDI engine calibrated for gasoline handles oxygenated fuels of butanol and ethanol.
- Previous work done focused on ethanol and more recently lower butanol blends. This data is a continuation of that work extending the baseline test plan to include higher alcohol blends of 1-butanol and iso-butanol.
- Limited engine test data for butanol is available in the literature.

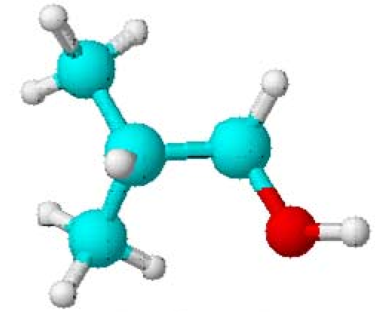
Important Fuel Properties



Ethanol



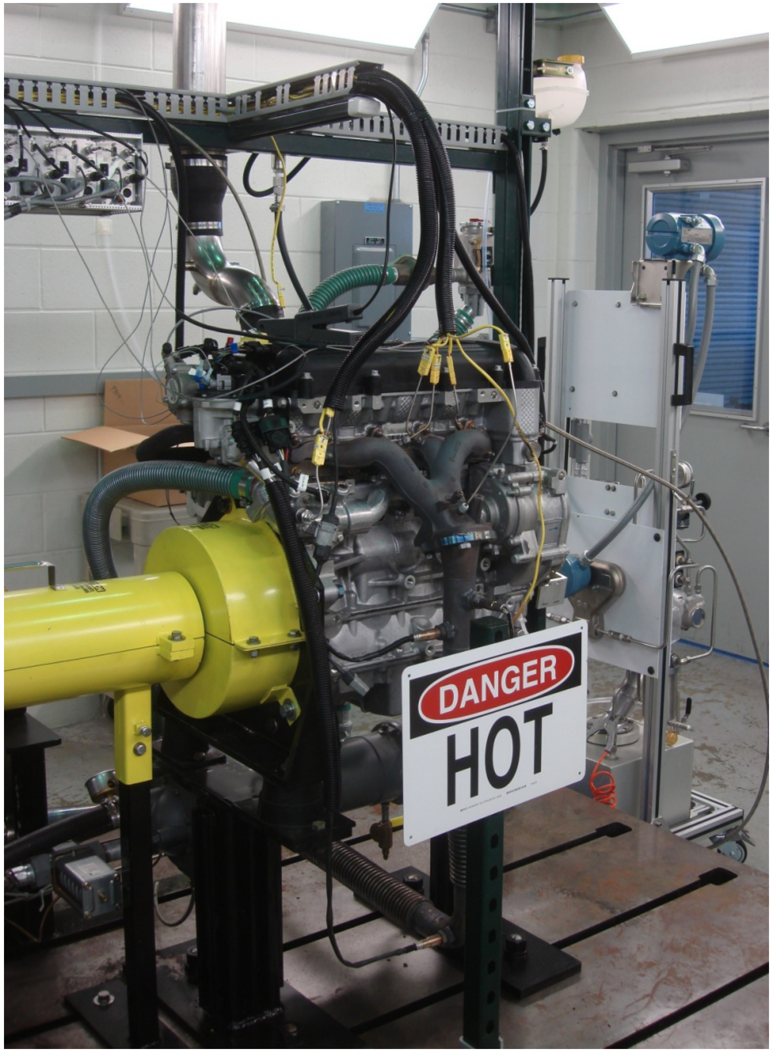
1-butanol



iso-butanol

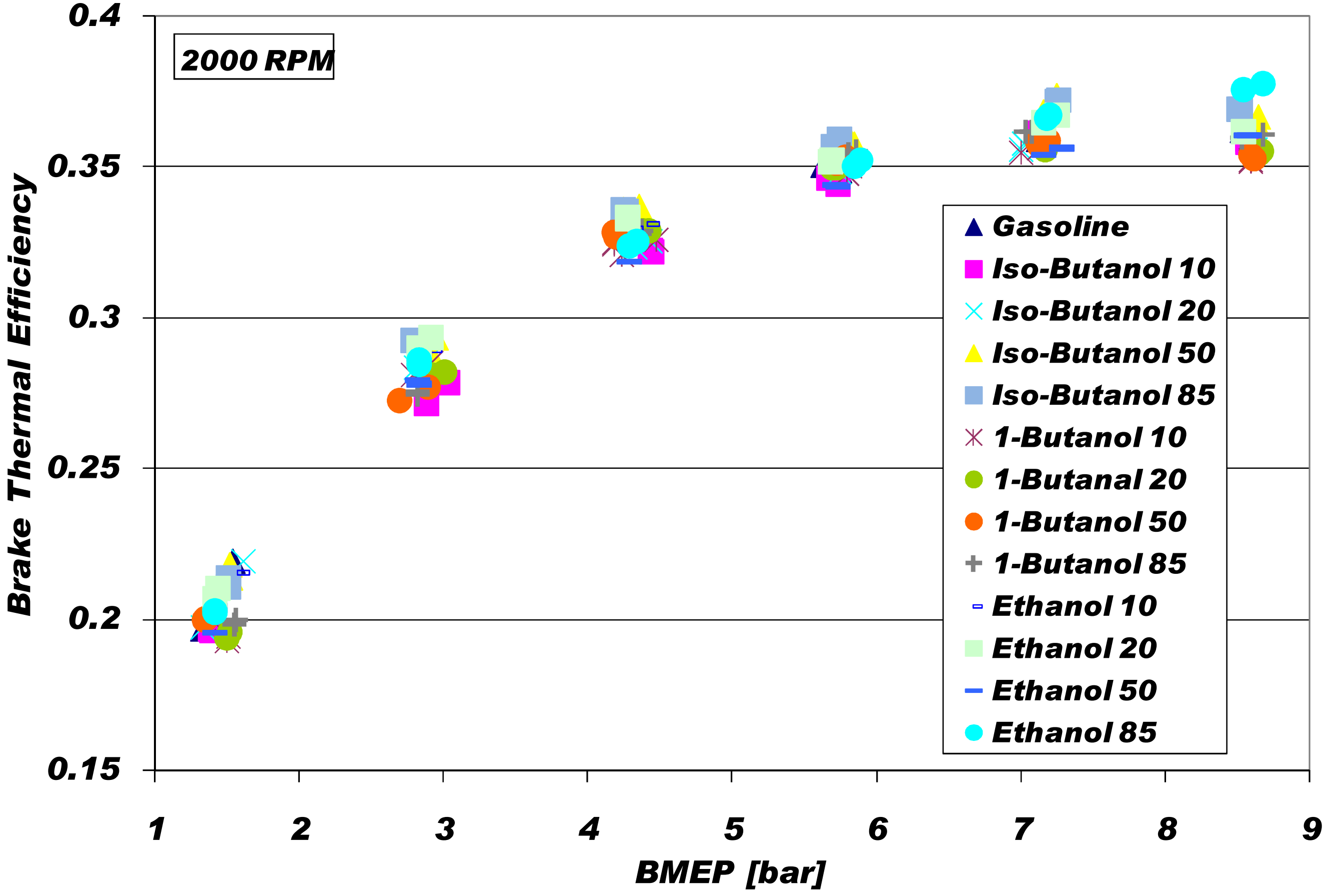
	Gasoline	Ethanol	1-butanol	Iso-butanol
Composition (C,H,O) (% mass)	86, 14, 0	52, 13, 35	65, 13.5, 21.5	65, 13.5, 21.5
RON	96	109	98	105
MON	78	90	84	91
Latent Heat of Vaporization (@25ºC) (kJ/kg)	380 - 500	919	706	686
Viscosity (@25ºC) (mPa)	0.881	1.10	2.544	4.132
Solubility in water	<.1	Fully miscible	7.7	7.6
Relative Energy Content (%)	100%	66%	85%	84%

Experimental Setup



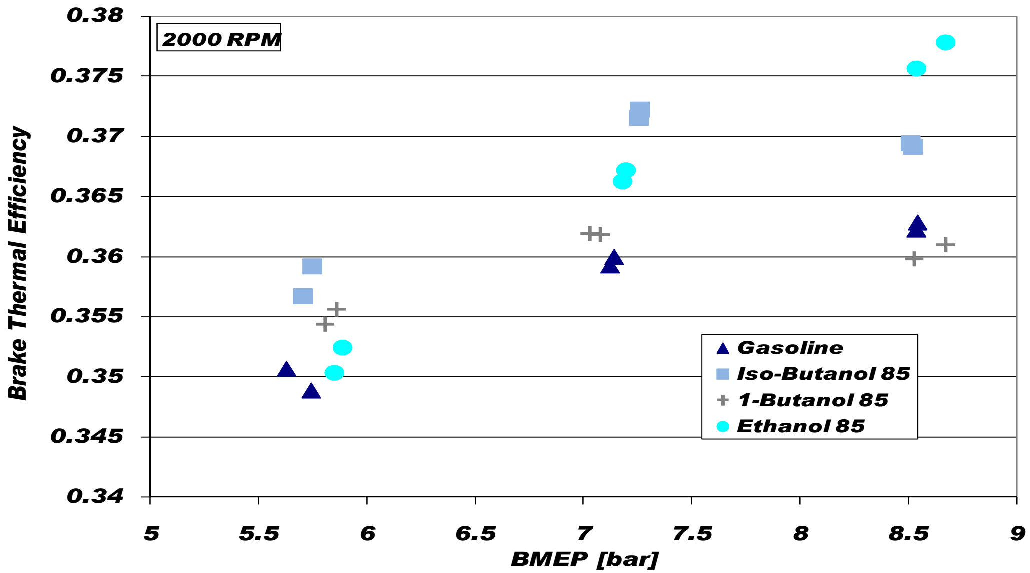
- Opel 2.2 l Ecotec Direct (SIDI) (GML850)
  - 4 – Cylinder
  - Direct Injection (homogeneous)
  - 4-valve DOHC
  - Electronic EGR control
  - Operates closed loop lambda control
  - 12:1 Compression ratio
  - Manufacturer recommended 95 RON fuel quality
  - Equipped with Knock sensor
  - Stock ECU calibrated for use with gasoline fuel
- Measurement
  - Cylinder Pressure
  - Fuel and Air mass flow
  - Engine out emissions with Horiba MEXA Model 7100D
  - Spark and injection

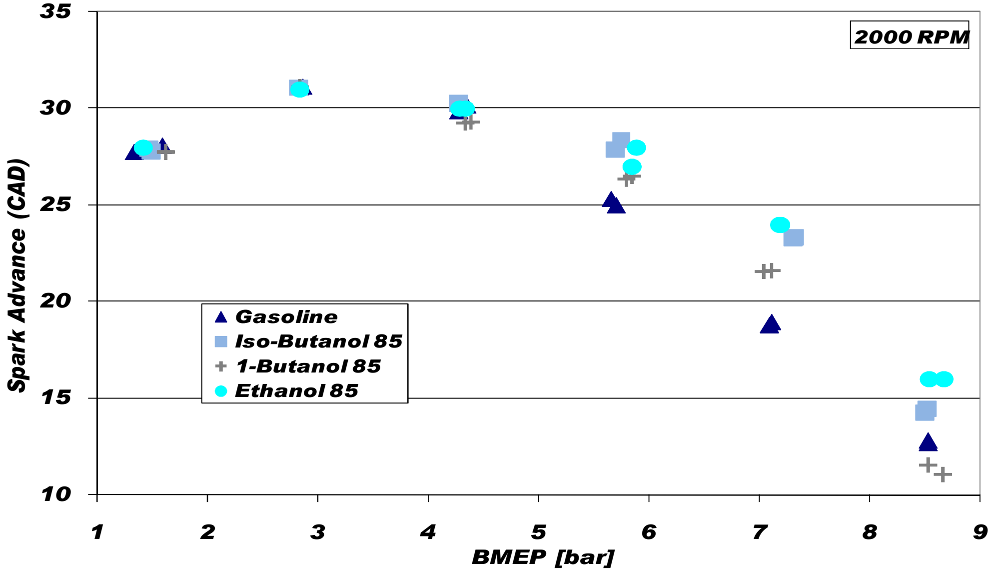
Brake Thermal Efficiency at 2000 RPM



- Results from this work find that engine efficiency and emissions are affected more by the engine controls over the type fuel used
- At low loads the difference in calculated efficiency among the fuels is difficult to determine
- At the high load condition, efficiency numbers are spread further apart.

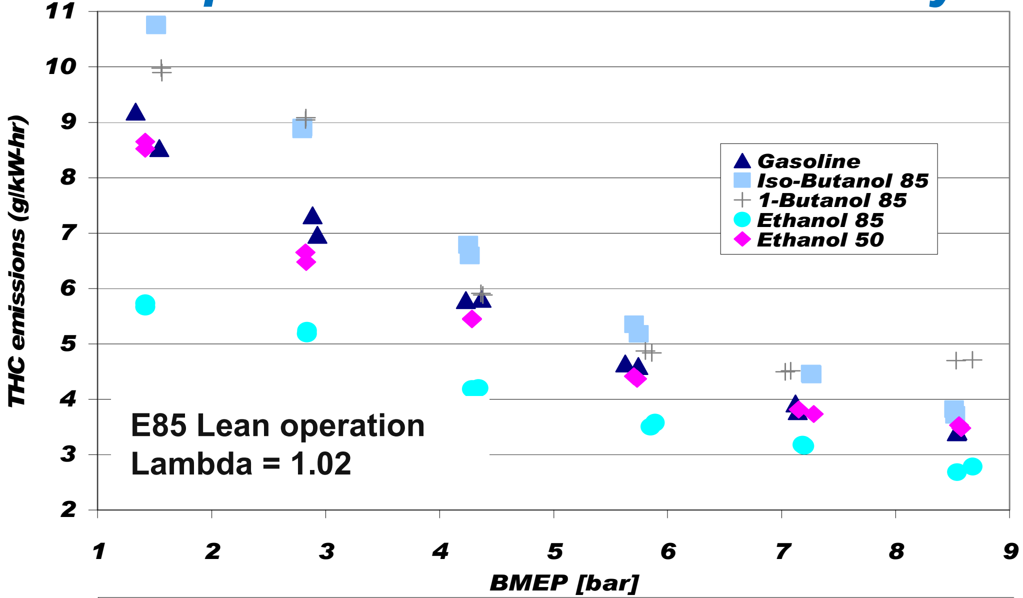
Effect of Fuel Octane Rating on Engine Thermal Efficiency

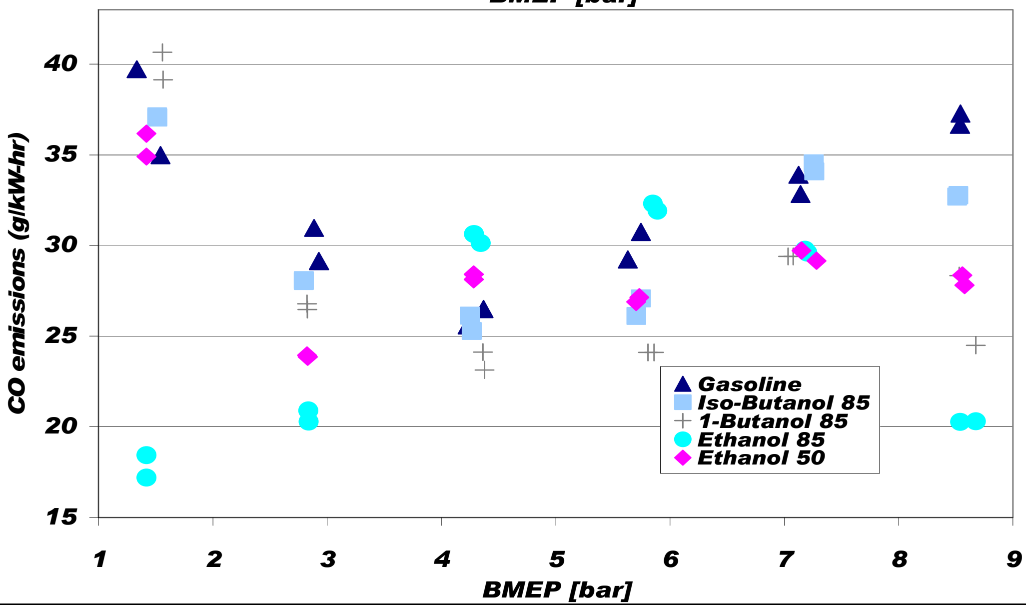




- Zoom in, we can see a consistent separation in the data and the higher alcohol blends are at the top of the efficiency range
- Engine equipped with a knock sensor that retards spark from the calibrated spark map.
- The results indicate at high load condition a relative efficiency advantage for ethanol and iso-butanol of about 2.5% over gasoline
- Data shows that there is no noticeable difference in spark timing for the different fuels at engine loads up to 4.3 bar.
- At high engine loads the influence of knock resistance between the different fuels is obvious.

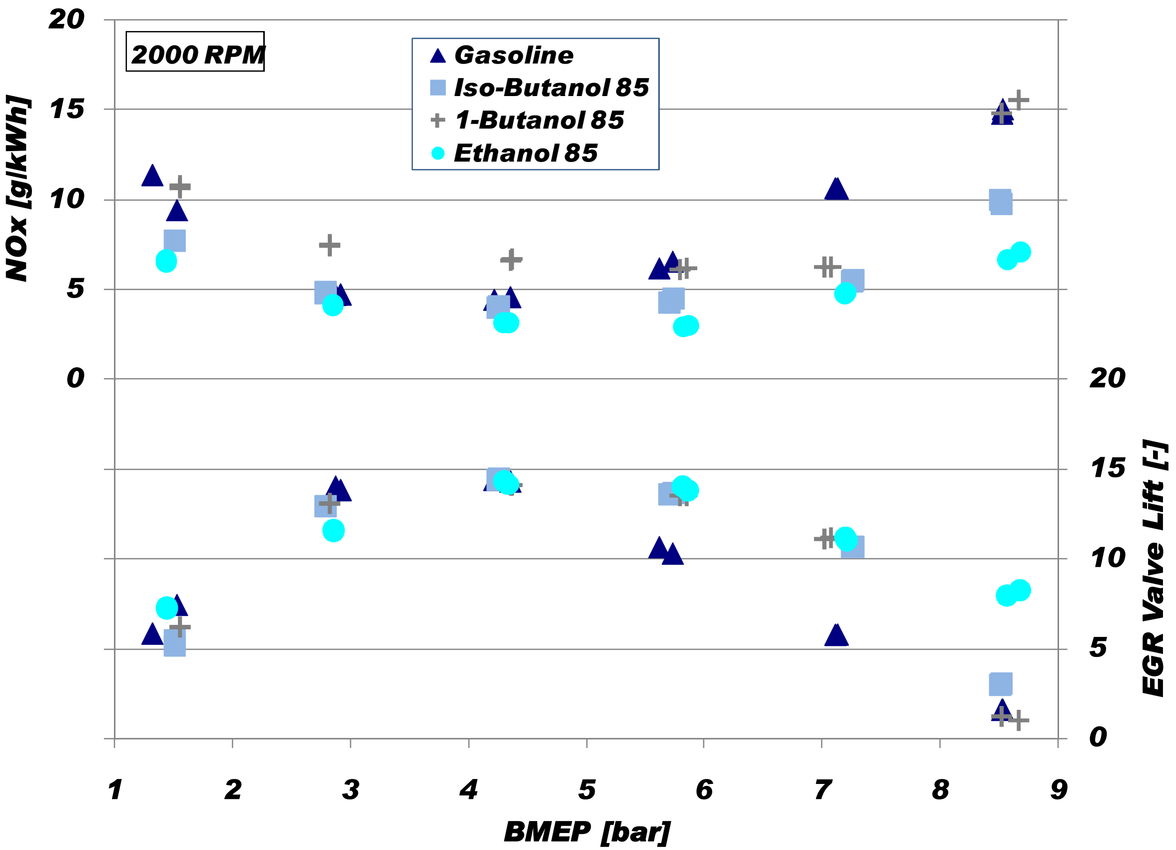
Comparison of CO and Total Hydrocarbon Emissions





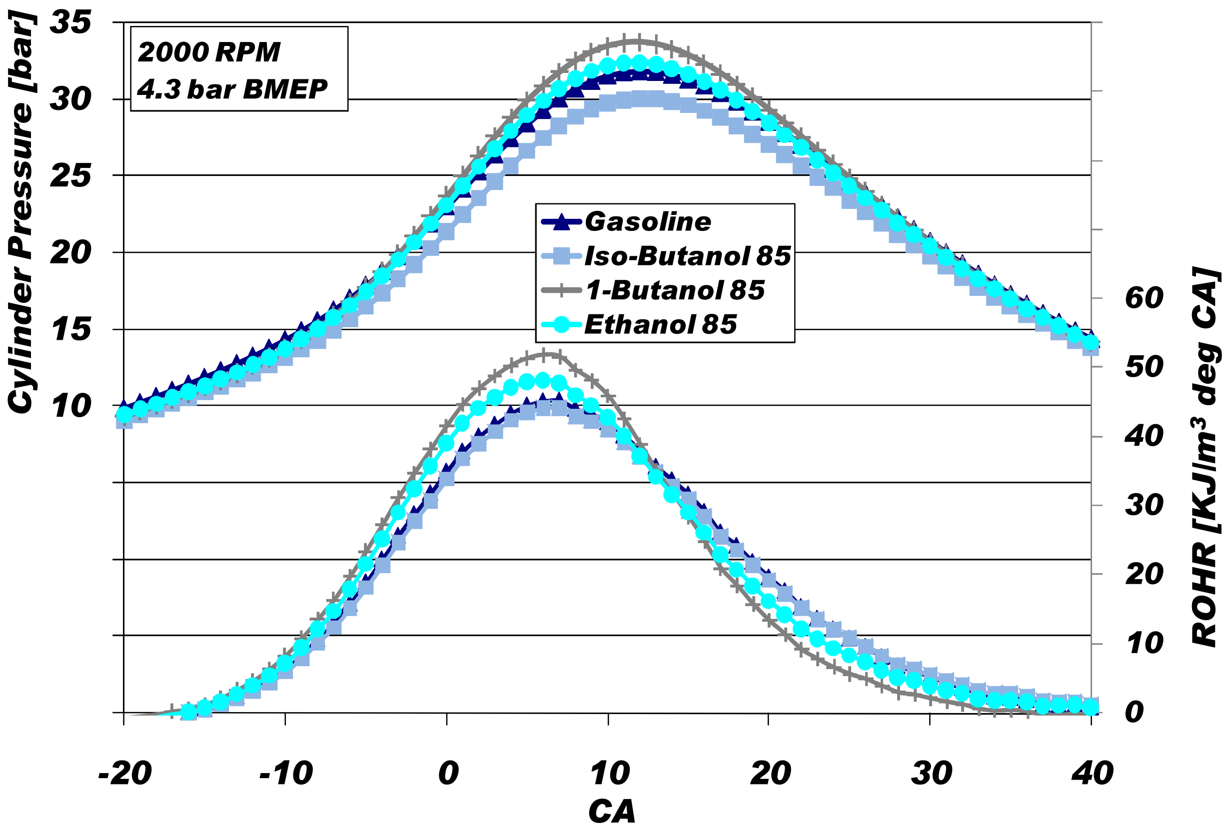
- Differences in Carbon Monoxide and Total Hydrocarbon emissions were not found to be attributable to differences in fuel properties but rather the lambda control strategy.
- Engine Controller has limits in deviating from the calibrated fuel map.
- These limitation were reached with E85 and resulted in the engine running at a slightly lean condition.

Comparison of NOx and EGR valve lift



- Relation ship of increased NOx formation with reduced exhaust gas recirculation.
- At increased load a larger separation of oxides of nitrogen exist which are mainly due to differences in the amount of EGR valve lift.
- Results show that 1-butanol has highest NOx output at low and mid loads and this is believed to be a result of peak cylinder pressure.

Average Peak Cylinder Pressure



- 1-butanol results in the highest peak cylinder pressure.
- ECU controlled spark timing remains the same at low and mid engine load due to absence of knock.
- ROHR shows shortest combustion duration and highest maximum rate of heat release for 1-butanol.
- Ethanol shows a shorter combustion duration as well as higher ROHR over gasoline which corresponds to higher flame speed of ethanol.

Conclusions

- Both 1-butanol and iso-butanol have a 17% higher energy content than ethanol which narrows the shortfall in vehicle fuel economy.

- Brake thermal efficiency at low and medium engine load up to 4.3 bar do not show any significant difference between butanol and ethanol fuel blends.

- At high engine loads ethanol and iso-butanol show advantages in brake thermal efficiency over gasoline. The increased Anti-Knock index of the higher blends of these fuels allows the ECU to maintain proper spark advance for appropriate combustion phasing.

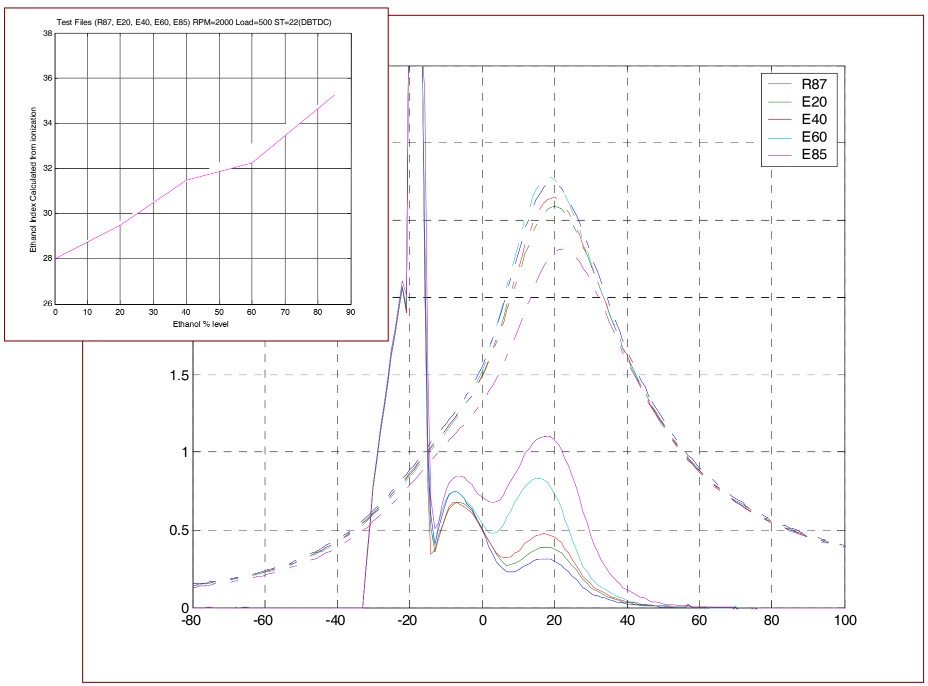
- A comparison of rates of heat release suggests that the flame speeds for 1-butanol are higher than ethanol. ROHR of iso-butanol and gasoline in the data are very similar. Actual flame speed values for butanol will be verified as part of future work.

Future Work

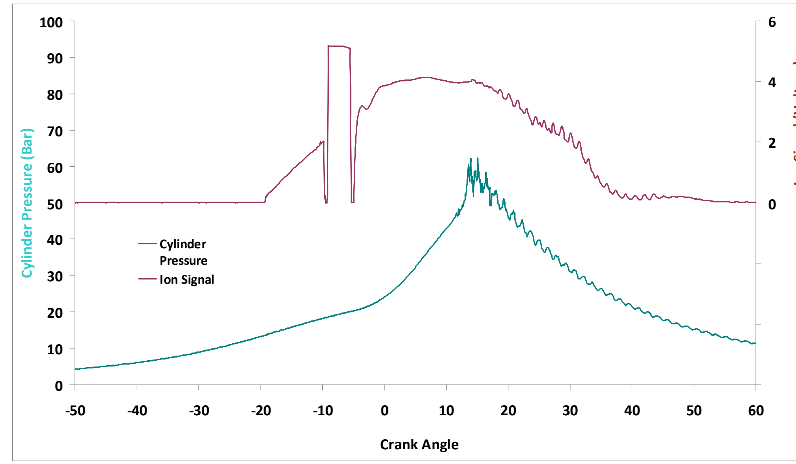
- Non-Regulated Emissions
  - Alcohol fuels are expected to show differences in emissions levels of currently non-regulated constituents.
  - An FTIR was used to collect the data of non-regulated emissions from ethanol and butanol, gasoline blended fuels.
- Combustion Sensing
  - Work is being done with Ion detection at the spark plug for use as a in-cylinder combustion feedback for control strategy to optimize combustion phasing.

The Ionization Sensor Allows for an
Ignition System with Combustion Feedback

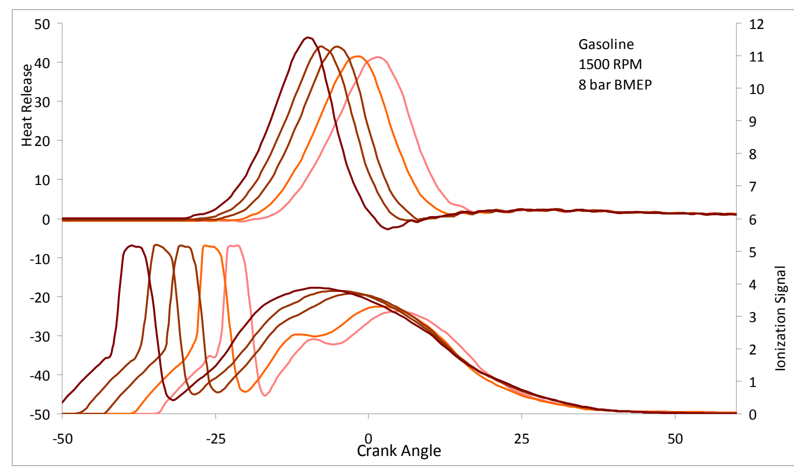
- Ionization signal is used to:
  - Infer fuel blend (% ethanol)
  - Determine combustion events and phasing
  - Knock detection



Fuel Blend Inference



Knock Detection



Spark Sweep to Show Combustion Phasing

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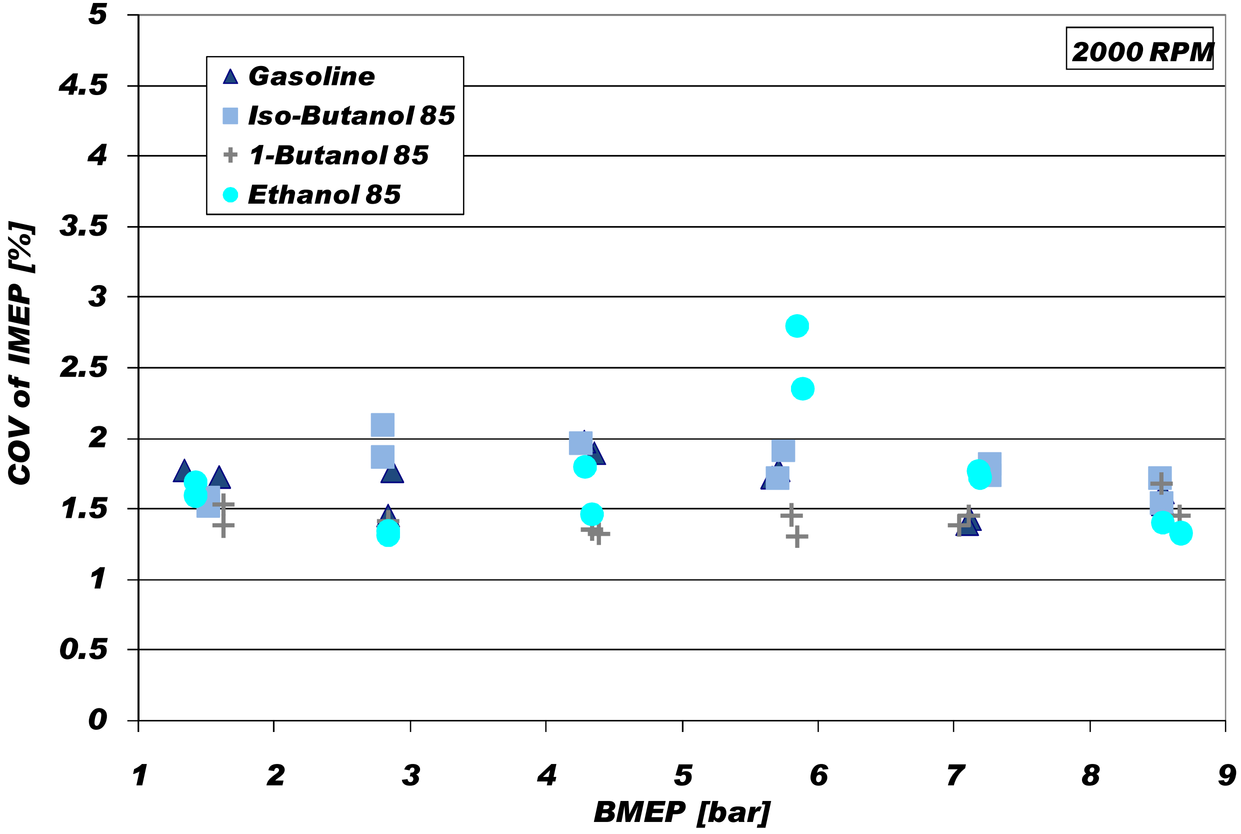
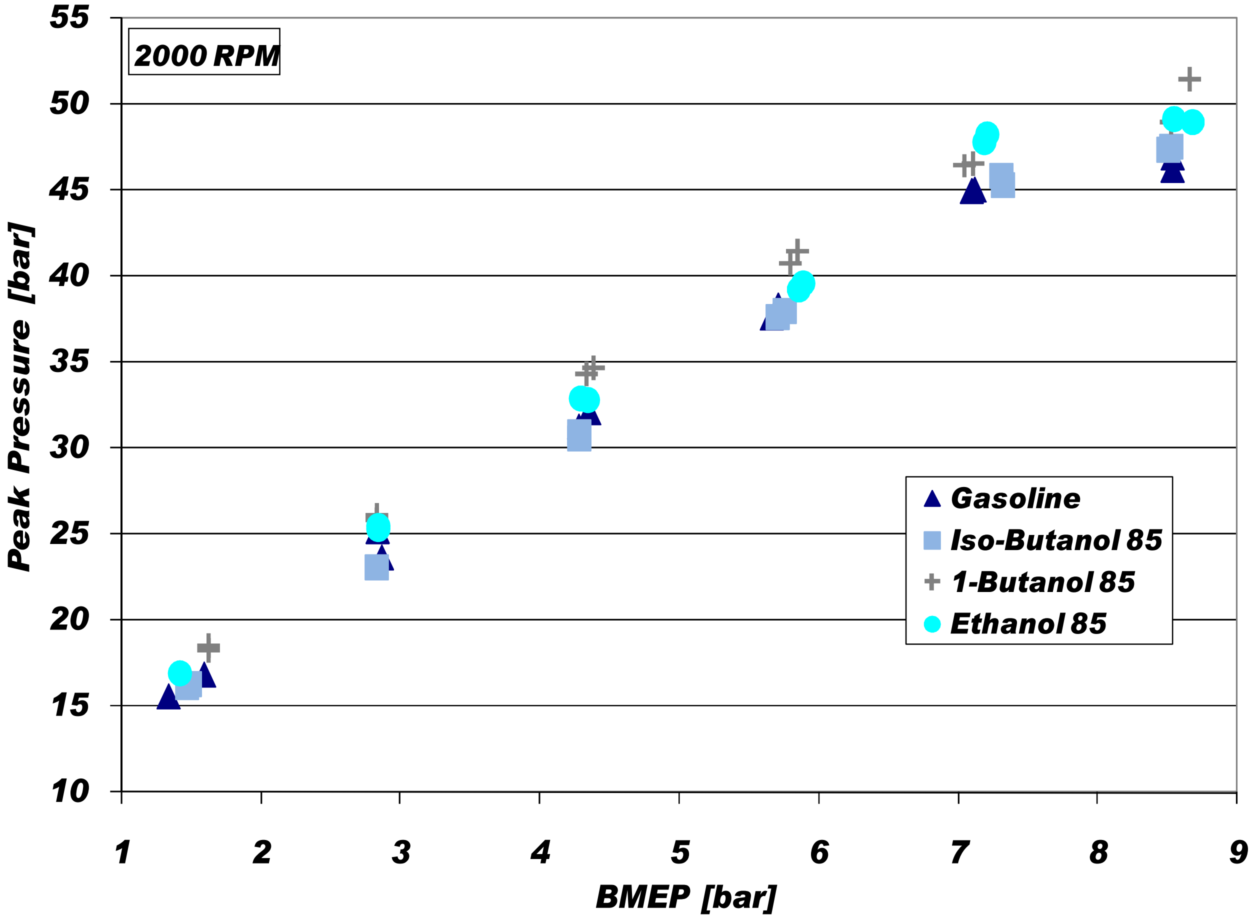


- It is important that use of alternative fuels does not compromise the combustion stability
- Combustion stability for all operating points with all fuels is below a value of 3 indicating a very stable combustion
- No trend suggests a deterioration of combustion stability with any of the alcohol fuels in comparison to the gasoline baseline.

Average Peak Cylinder Pressure



- At low load peak cylinder pressure correspond well with NOx formation
- At higher engine load the trends are not as easily traceable because of significant differences in spark timing.
- ECU controlled spark timing remains the same at low and mid engine load due to absence of knock.
- Results show that 1-butanol has highest NOx output at low and mid loads and this is believed to be a result of peak cylinder pressure faster burn rate.