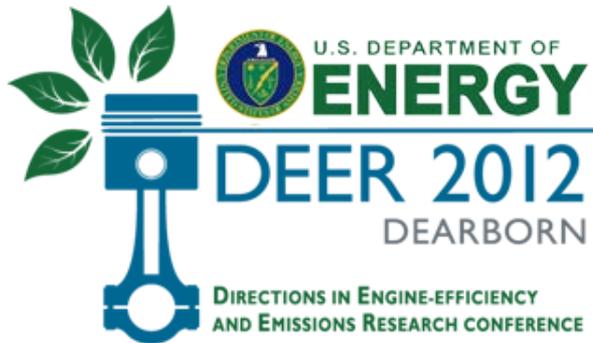


THE IMPACT OF LOW OCTANE HYDROCARBON BLENDING STREAMS ON “E85” ENGINE OPTIMIZATION

Jim Szybist and Brian West

Oak Ridge National Laboratory

October 19, 2012



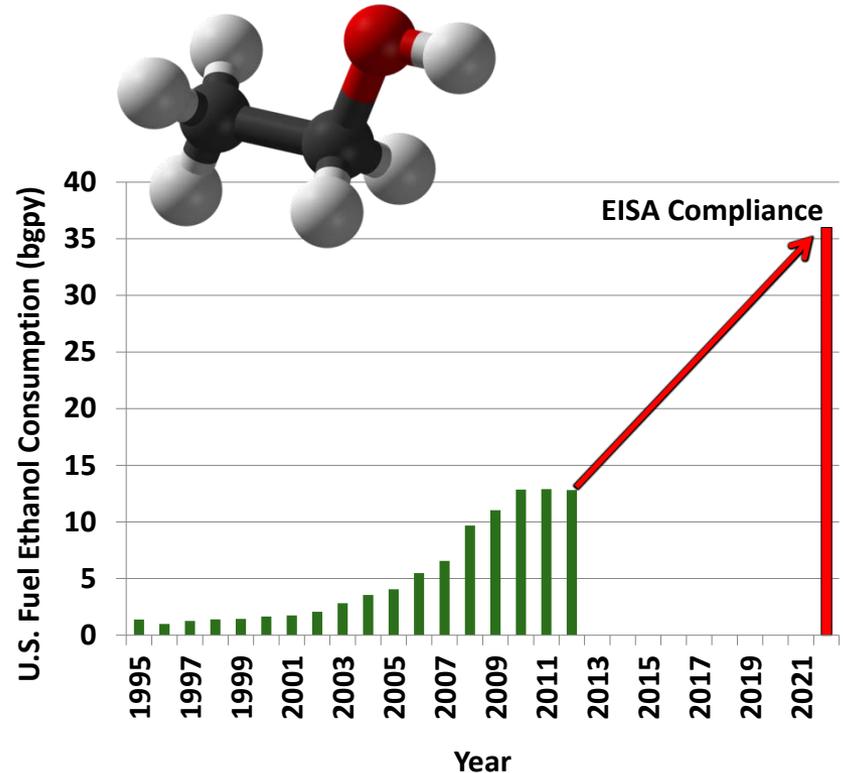
Acknowledgement

This research was supported by the US Department of Energy (DOE) Office of Vehicle Technology under the Fuels & Lubricants Program managed by Kevin Stork and Steve Przesmitzki.



ETHANOL IS CURRENTLY THE LARGEST VOLUME BIOFUEL, VERY IMPORTANT FOR EISA COMPLIANCE

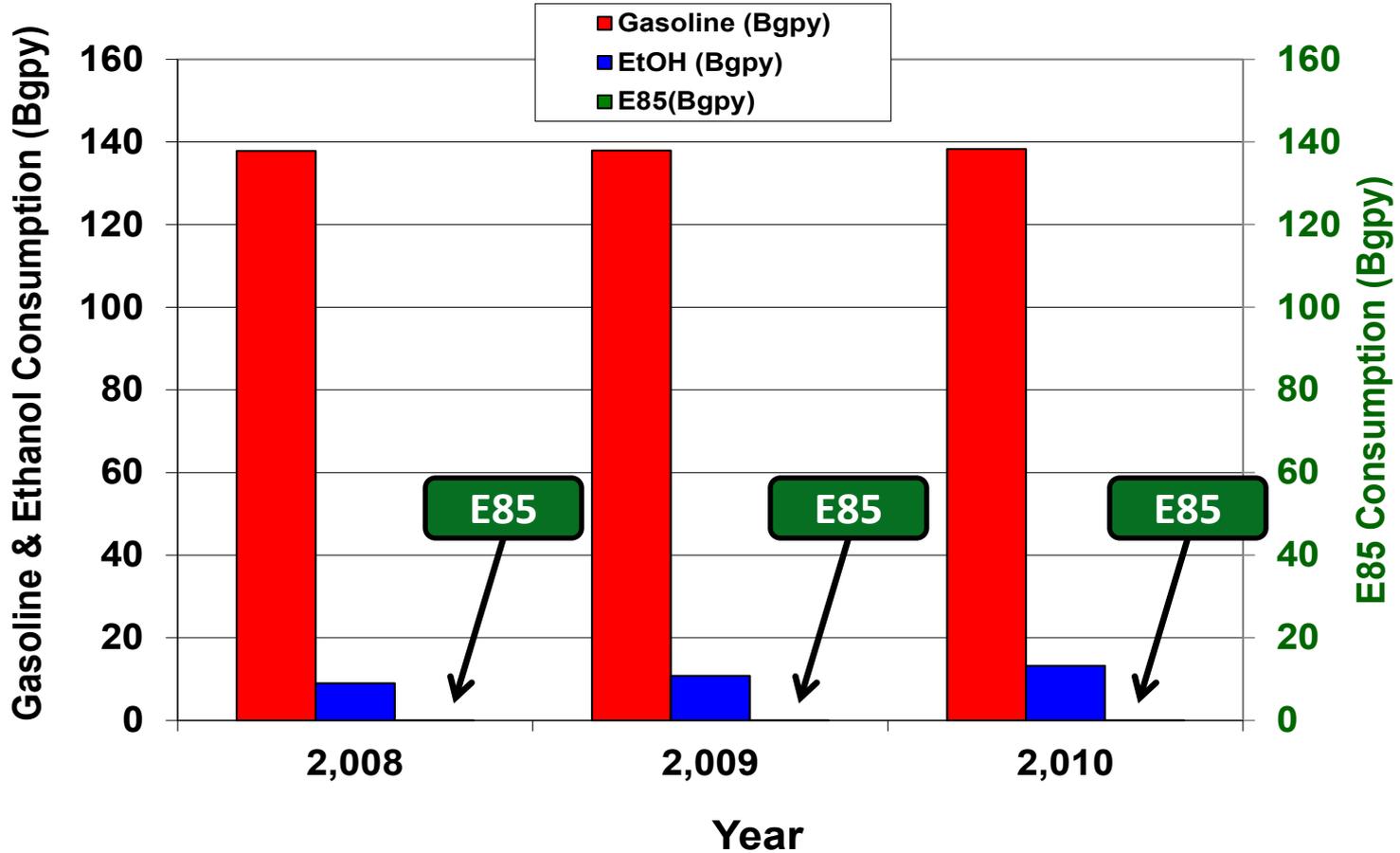
- **Dramatic growth in ethanol use in last 10 years (over 10 billion gallons per year (bgpy))**
- **January 2007 – President launches 20-in-10**
 - Spring 2007 – DOE kicks off intermediate blends studies
- **December 2007 – EISA sets national goals for biofuel use**
 - 36 bgpy by 2022
- **Essentially hit E10 “blend wall” in 2010**
 - E15 blends increase “blend wall” ceiling by up to 7 bgpy by 2022
- **Large untapped potential with “E85” or other high ethanol blend**



*U.S. Ethanol consumption.
Data from Energy Information Agency
<http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf>

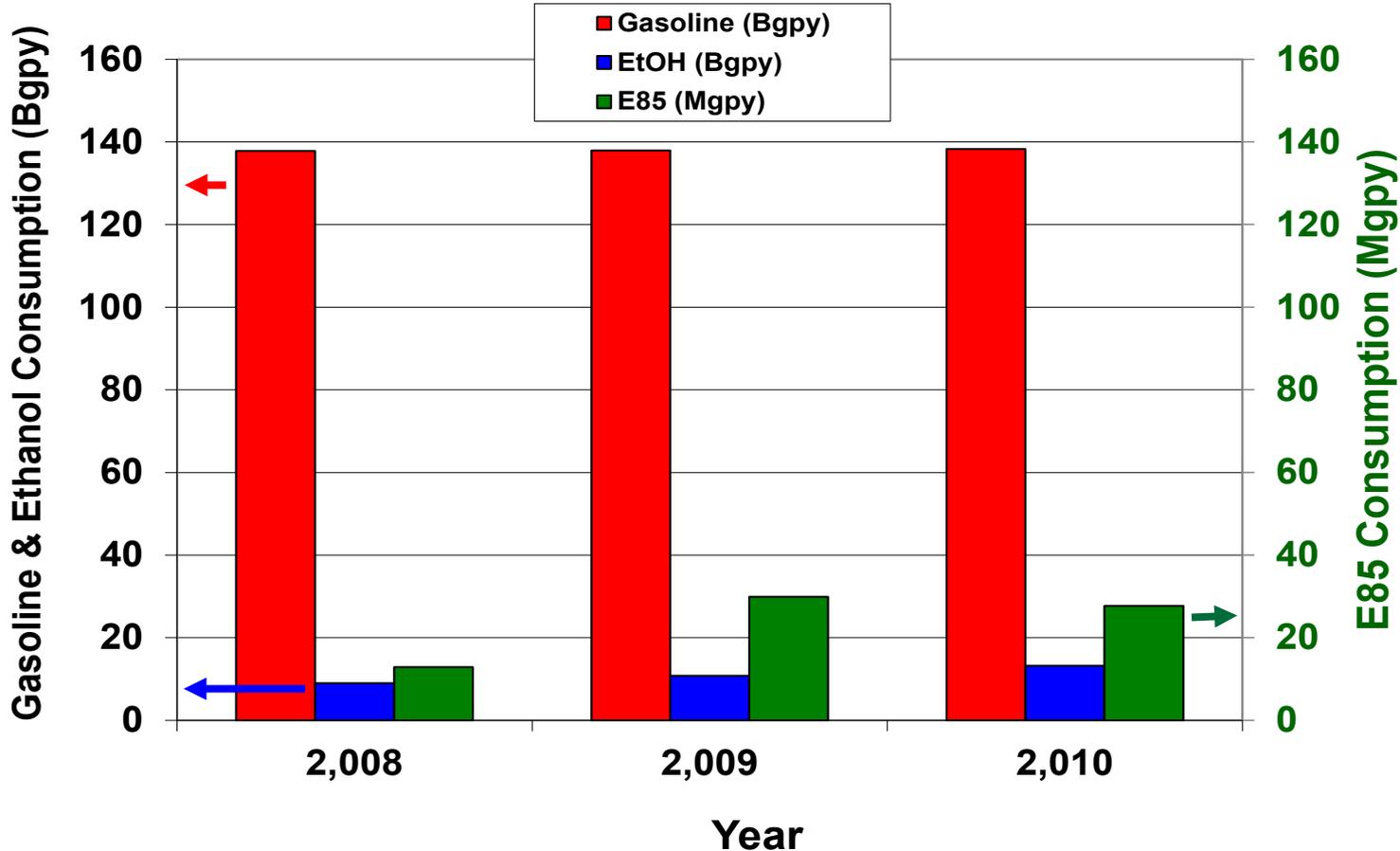
**2012 extrapolated from 6 months of data

LARGE UNTAPPED POTENTIAL OF E85



- Over 8 million FFVs, currently consume less than 0.03 Bgpy

LARGE UNTAPPED POTENTIAL OF E85 (NOTE CHANGE IN UNITS)



- Over 8 million FFVs, currently consume less than 0.03 Bgpy

Potential for additional 4-7 Bgpy ethanol utilization (TODAY)*

(Could exceed 20Bgpy by 2022)**

*Assumes 8M veh, 12-15k mi/yr, 13-18 mpg

**Assumes additional 2.5M FFV/yr added to fleet

MORE E85 PUMPS AND NUMBER OF FFVs ARE IMPORTANT BUT...

Consumers are not choosing E85 when it is available

- Gasoline/E10 pumps average ~2400 gallons per day
- E85 dispenser pumps average 40 gallons per day
 - ❑ More than 8 million FFVs on the road
 - ❑ **Average FFV consumes less than 4 gallons E85 per year!**

Numerous reasons for lack of E85 consumer acceptance

- Lower Energy Density and higher \$/BTU (compared to gasoline or E10)
 - Shortened range
 - Higher cost per mile
- How much ethanol is in my “E85?”
 - ASTM specification allows 51% to 83% ethanol primarily to control volatility of blends
 - Potentially high variability in vehicle range (as ethanol content fluctuates)
 - May contribute to consumer confusion



OPTIMIZATION POTENTIAL OF HIGH ETHANOL FUEL BLENDS FOR EFFICIENCY AND PERFORMANCE HAS BEEN THOROUGHLY DOCUMENTED

SAE International

Investigation of Knock Limited Compression Ratio of Ethanol Gasoline Blends

2010-01-0619
Published
04/12/2010

James Saybut

SAE International

Spray Characterization of Ethanol Gasoline Blends and Comparison to a CFD Model for a Gasoline Direct Injector

2010-01-0601
Published
04/12/2010

Nakan Yimaz
Robert Knack LLC

SAE International

Parameter Optimization of a Turbo Charged Direct Injection Flex Fuel SI Engine

2009-01-0238

Mark J. Christie and Nicholas Fortino
Piacato, Inc.

Hakan Yilmaz
Robert Knack LLC

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SAE International

Study on Boosted Direct Injection SI Combustion with Ethanol Blends and the Influence on the Ignition System

2011-36-0196

Paulo Gomes, Rainer Ecker, Andre Kulzer, Andreas Kuffrauh, Ederson Costi
Robert Knack GmbH, Stuttgart

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SAE International

Engine Efficiency Improvements Enabled by Ethanol Fuel Blends in a GDI VVA Flex Fuel Engine

2011-01-0900
Published
04/12/2011

Wayne Moore, Matthew Foster, and Kevin Hoyer

SAE International

The Effect of Ethanol Fuel on a Spark Ignition Engine

2006-01-3380

Koichi Nakata, Shintaro Utsui, Atsuharu Ota, Katsunori Kawatsuka, Takashi Kawai and Takashi Tsunooka
Toyota Motor Corporation

SAE International

A Study of Alcohol Blended Fuels in an Unthrottled Single Cylinder Spark Ignition Engine

2010-01-0618
Published
04/12/2010

Abdoul Cairn and Alan Todd

SAE International

Effect of Ethanol on Knock in Spark Ignition Gasoline Engines

2009-02-2008 (SAE) / 2009-07-1042

Kenjiro Nakamura
Gazoli Motor Corporation
Jin Kosaka and Yasuhiko Daiho
Wazawa University

SAE International

Effect of Heat of Vaporization, Chemical Octane, and Sensitivity to Knock Limit for Ethanol - Gasoline Blends

2008-01-0216

Robert A. Stein, Dusan Polovina and Kevin Rob
AVL Performance Engineering Inc.

SAE International

Charge Cooling Effects on Knock Limits in SI DI Engines Using Gasoline/Ethanol Blends: Part 2-Effective Octane Numbers

2008-01-0216

Emmanuel Kasseris and John Heywood
Siemens Automotive Laboratory, MIT

SAE International

Optimal Use of E85 in a Turbocharged Direct Injection Engine

2008-01-1402

Robert A. Stein, Christopher J. House and Thomas G. Leone
Ford Motor Company

SAE International

Ethanol Detection in Flex-Fuel Direct Injection Engines Using In-Cylinder Pressure Measurements

2009-01-0407

Nestor Oliverio and Anna Stefanopoulou
University of Michigan
Li Jiang and Hakan Yilmaz

SAE International

A Simulation Method to Guide DISI Engine Redesign for Increased Efficiency using Alcohol Fuel Blends

2010-01-1203
Published
04/12/2010

JSAE 2007-0779
SAE 2007-01-2037

Satoshi Taniguchi, Kaori Yoshida, Yukihiko Tsukasaki
Toyota Motor Corporation

SAE International

Charge Cooling Effects on Knock Limits in SI DI Engines Using Gasoline/Ethanol Blends: Part 1-Quantifying Charge Cooling

2010-01-1275
Published
04/12/2012

James J. Engle, Jon S. Olson and Sauri S. Sharma
Ford Motor Company

SAE International

Development of a Naturally Aspirated Spark Ignition Direct-Injection Flex-Fuel Engine

2008-01-0216

Craig D. Marriott, Matthew A. Wiles and J. Michael Goff
General Motors Advanced Powertrain

Scott E. Pariah
General Motors Research & Development

SAE International

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Li Jiang and Hakan Yilmaz

SAE International

A Comparison of the Effect of E85 vs. Gasoline on Exhaust System Surface Temperature

2007-01-1392

James J. Engle, Jon S. Olson and Sauri S. Sharma
Ford Motor Company

SAE International

Characterization of Multi-hole Spray and Mixing of Ethanol and Gasoline Fuels under DI Engine Conditions

2010-01-2151
Published
10/23/2010

Atsushi Matsumoto, Yi Zhang and Xing-Bin Xie
Wayne State Univ.
Mag-Chia Lai
Wayne State Univ.
Wayne Moore
Delphi Energy & Engine Mgmt. Systems

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Feasibility Study of Ethanol Applications to A Direct Injection Gasoline Engine

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Satoshi Taniguchi, Kaori Yoshida, Yukihiko Tsukasaki
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The Impact of RON on SI Engine Thermal Efficiency

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SAE 2007-01-2007

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Daisuke Uchida, Atsuharu Ota, Shintaro Utsui, Katsunori Kawatsuka
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Ethanol Direct Injection on Turbocharged SI Engines - Potential and Challenges

2007-01-1408

P. E. Kapsas, A. Fuerhapter, H. Fuchs and G. F. Fraidl
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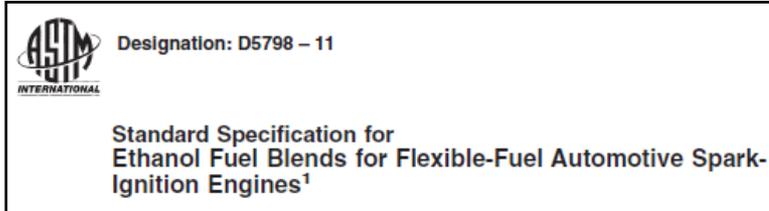
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P. E. Kapsas, A. Fuerhapter, H. Fuchs and G. F. Fraidl
AVL, Liechtenstein

Changes to ASTM D5798 have possible ramifications on “E85” fuel quality and optimization potential

Background: 2011 ASTM standard modifies previous specifications for E85



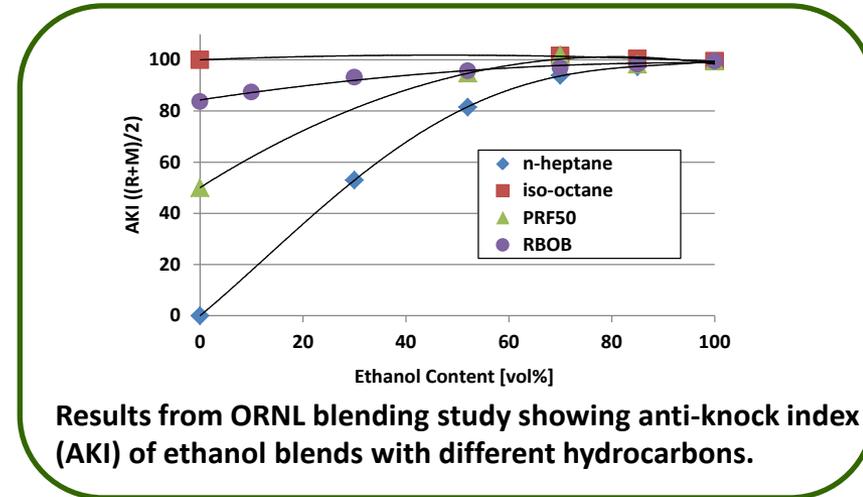
- **Potential for lower octane number fuel**

- Lower ethanol content (as low as 51 vol%)
- Low octane number refinery hydrocarbon streams
- No minimum octane number requirement

- **Earlier ORNL blending study revealed sufficiently high octane number sufficient for current FFV’s**

- **Numerous DOE-funded projects have shown potential for E85-optimized engines**

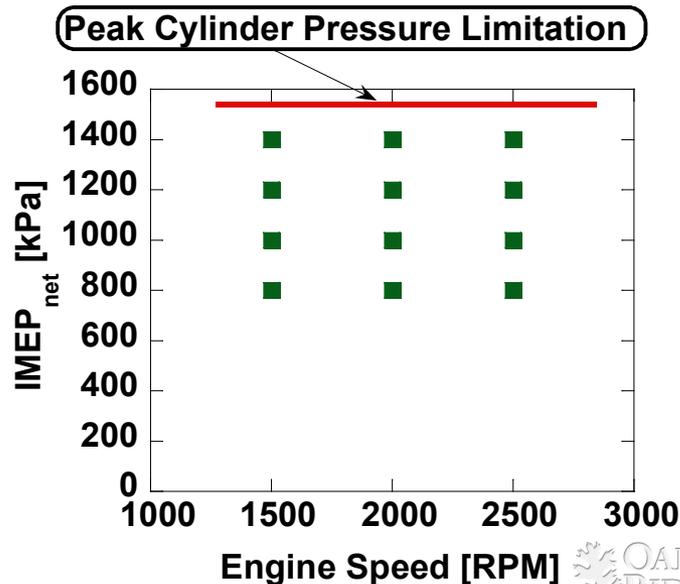
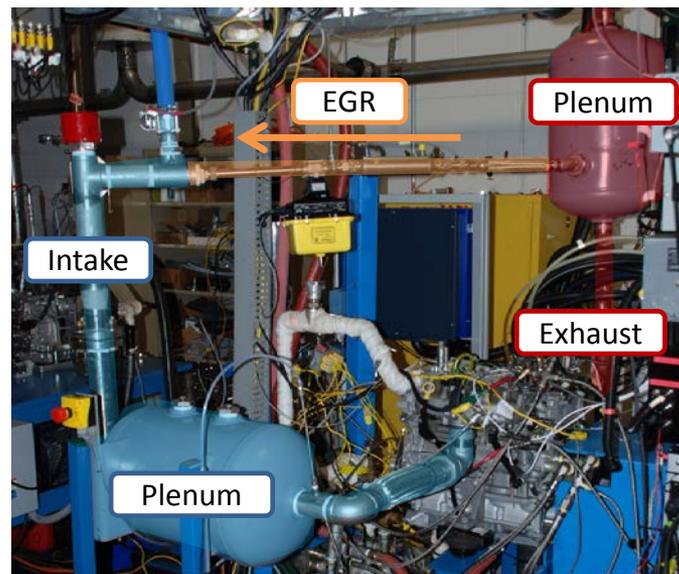
- High latent heat of vaporization and octane number are the basis for optimization
- Engine technologies: direct injection fueling, high compression ratio, boosted air handling for engine downsizing
- Impact of current fuel standard on potential for optimization is unclear



Objective: Experimentally determine impact of lower ethanol content and low octane hydrocarbon streams on ethanol-optimized engine

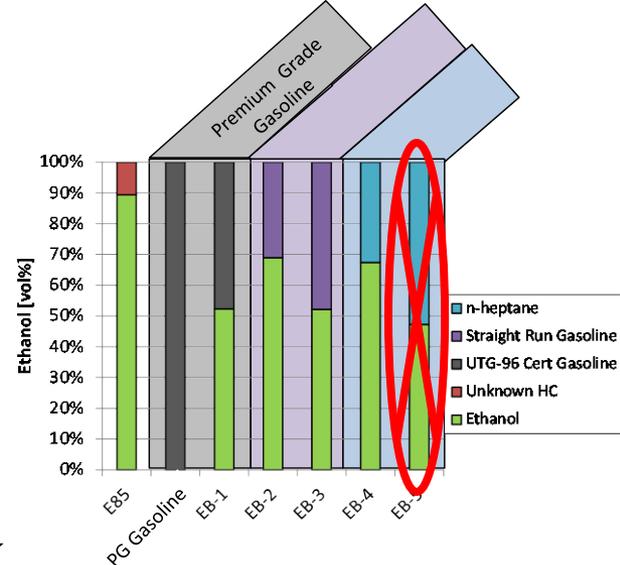
EXPERIMENTAL APPROACH: EVALUATE PERFORMANCE OF HIGH ETHANOL CONTENT FUELS WITH LOW OCTANE NUMBER HCs AT KNOCK-PRONE CONDITIONS

- **Single cylinder engine with hydraulic valve actuation (HVA)**
 - Modified 2.0L GM Ecotec engine (bore x stroke = 86mm x 86 mm)
 - High compression ratio (12.9:1), direct injection fueling, boost
 - DRIVEN controller for engine management
- **Knock-prone operating conditions**
 - Low speed (1500 to 2500 rpm)
 - High load (8 to 14 bar IMEP_{net})
- **Optimal combustion phasing except under knock-limited conditions**
 - Optimal phasing: CA50 = 8-9 CA aTDC_f
 - Combustion phasing retarded to mitigate knock



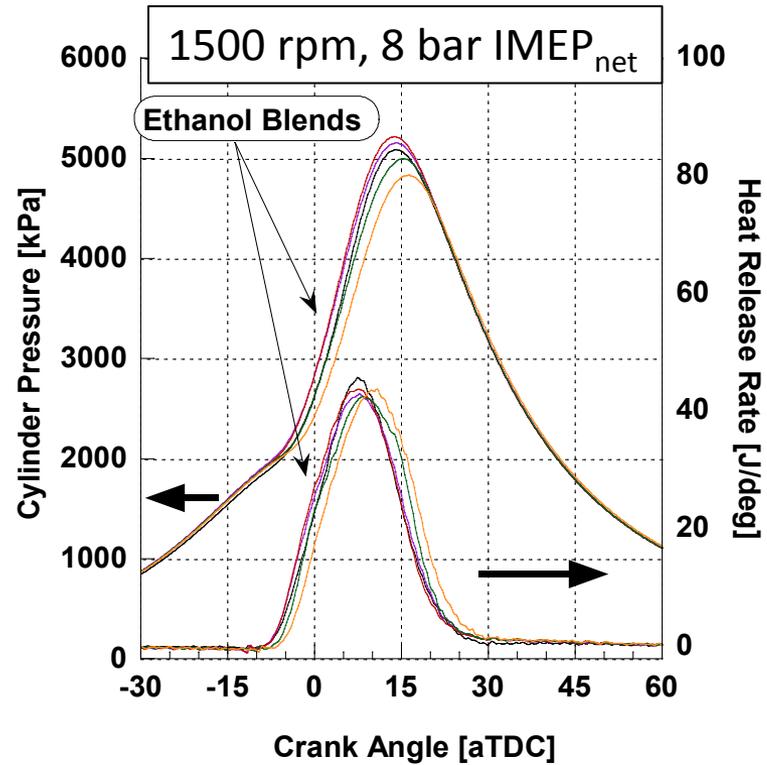
HYDROCARBON STREAMS WITH WIDE RANGE OF OCTANE NUMBER BLENDED WITH ETHANOL

- Ethanol splash blends made with either 51 or 67 vol% ethanol
- Hydrocarbons span a wide range of octane numbers
 - Premium grade gasoline: AKI = 92.2
 - Straight run gasoline: AKI = 63.6
 - n-heptane: AKI = 0



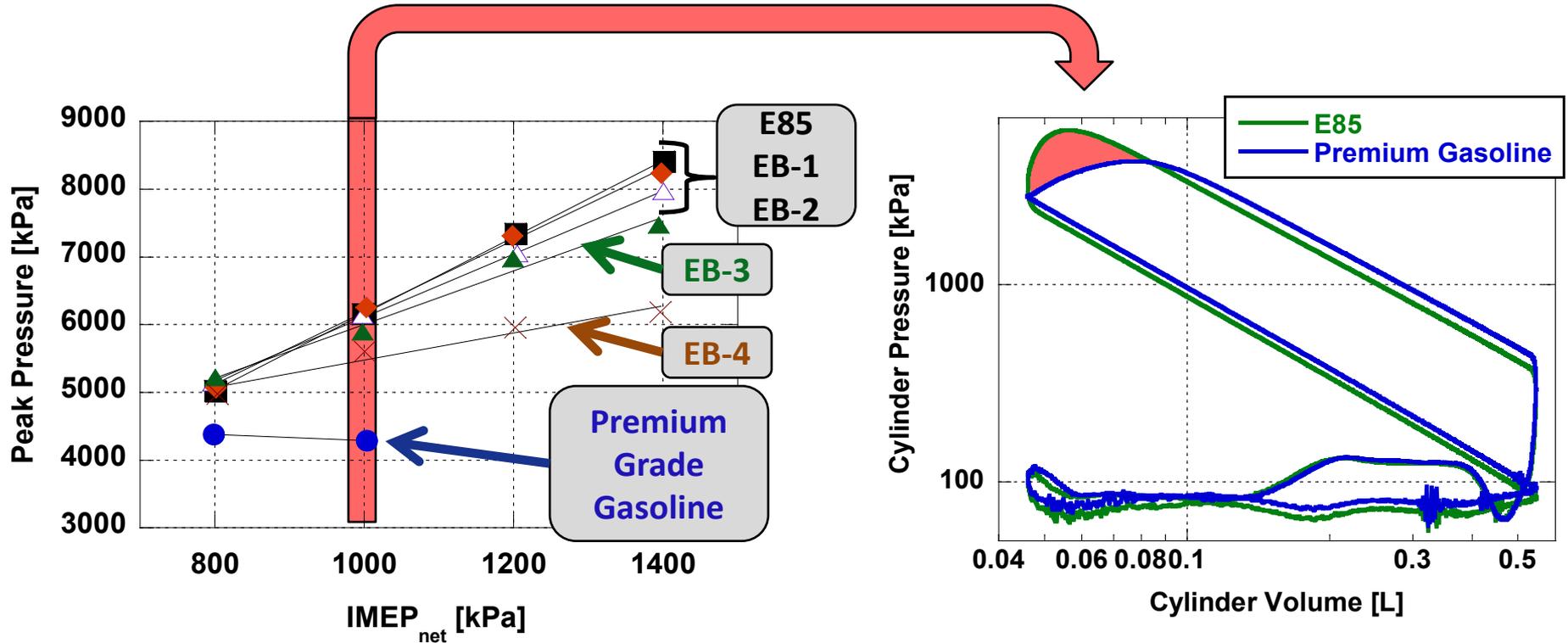
	100% Ethanol	Premium Gasoline	E85	EB-1	EB-2	EB-3	EB-4	EB-5
Hydrocarbon Type	100% Ethanol	Premium Gasoline	Undefined	Premium Gasoline	SRG	SRG	n-heptane	n-heptane
Ethanol content [vol%]	ASTM D5599	--	89.33	52.3	68.9	52.19	67.4	47.3
Reid Vapor Pressure [psi]	ASTM D5191	8.9	5.12	8.68	8.09	9.34	3.44	3.68
Oxygen content [wt%]	ASTM D5599	--	31.22	18.76	25.24	19.65	24.56	17.67
Carbon wt/%	ASTM D5291	86.83	56.22	67.83	60.82	65.62	61.45	66.82
Hydrogen wt/%	ASTM D5291	13.2	12.92	13.10	13.78	14.28	13.92	14.48
Specific Gravity	ASTM D4052	0.739	0.788	0.768	0.753	0.732	0.756	0.788
Octane nr (R+M)/2	N/A	92.2	96.9	97.5	96.5	95.0	93.5	81.2
Research Octane Number	ASTM D2699	96.1	105.0	104.4	101.1	102.0	100.4	84.8
Motor Octane Number	ASTM D700	88.2	88.7	90.5	88.9	88.0	86.2	77.6
Octane Sensitivity	N/A	7.9	16.3	13.9	15.2	14.0	14.2	7.2
Lower heating value/MJ/kg	ASTM D240	43.286	29.051	34.186	33.608	34.363	32.103	35.092
Stoichiometric AFR/-	N/A	14.42	9.45	11.45	10.58	11.57	10.72	11.94
Initial Boiling Point [°C]	ASTM D86	33.9	33.9	35.0	41.1	40.6	70.6	70.6
10% Distillation [°C]	ASTM D86	50.0	50.0	57.2	55.0	50.6	71.1	71.1
50% Distillation [°C]	ASTM D86	107.2	107.2	76.7	76.7	67.8	73.3	71.1
90% Distillation [°C]	ASTM D86	185.0	185.0	168.3	168.3	168.3	168.3	168.3
Final Boiling Point [°C]	ASTM D86	185.0	185.0	168.3	168.3	168.3	168.3	168.3

ALL ETHANOL FUEL BLENDS EXHIBIT SUPERIOR KNOCK RESISTANCE RELATIVE TO PREMIUM GRADE GASOLINE



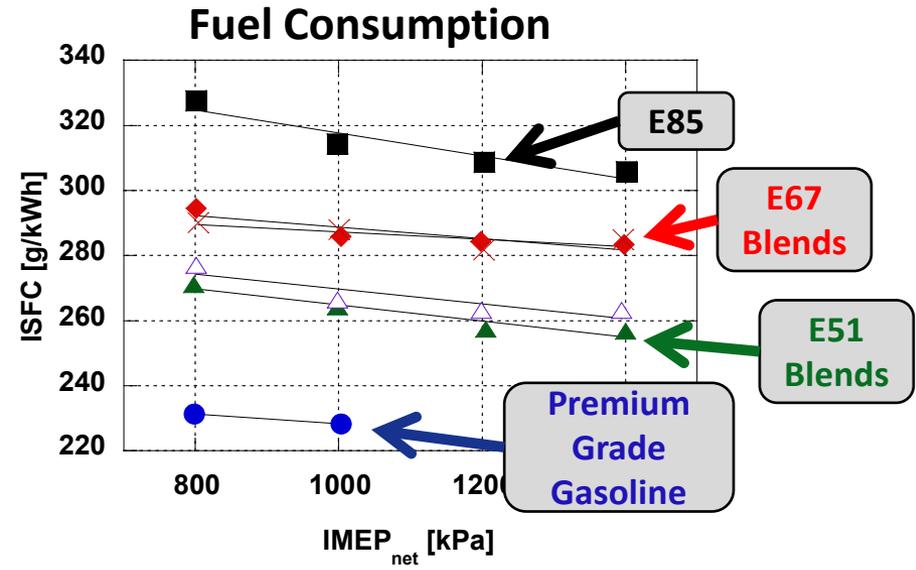
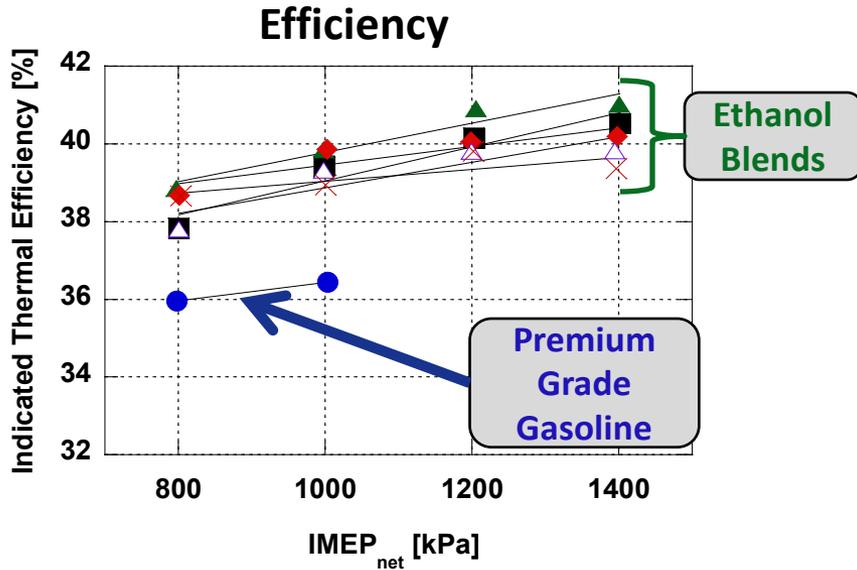
Spark timing used to retard combustion phasing for knock mitigation

RETARDED COMBUSTION PHASING DECREASES PEAK CYLINDER PRESSURE AND INCURS AN EFFICIENCY PENALTY



- Peak cylinder pressure naturally increases with engine load
- When phasing is retarded to mitigate knock, peak cylinder pressure is reduced
 - Nearly 1/3 reduction in peak cylinder pressure for premium grade gasoline at 1000 kPa IMEP_{net}
- Results in less work per unit energy of fuel due to underutilized expansion stroke

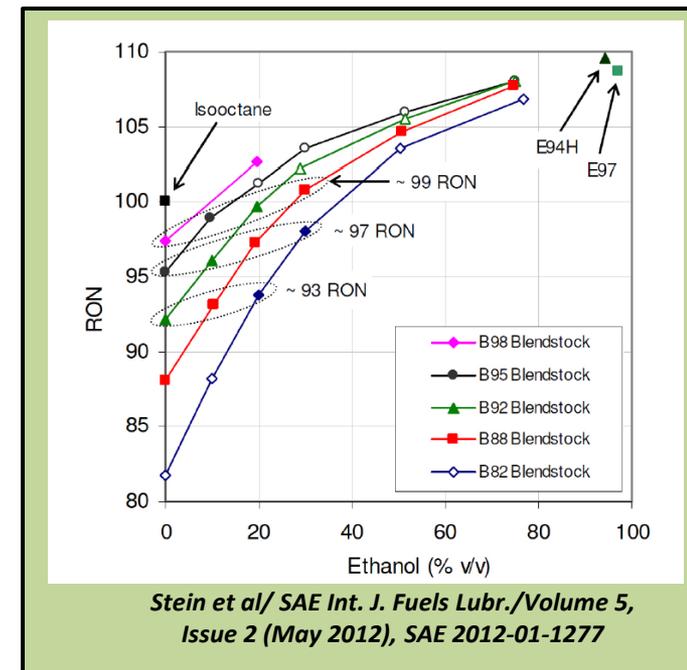
RETARDED PHASING FOR PREMIUM GRADE GASOLINE IS THE PRIMARY REASON FOR SUBSTANTIALLY LOWER THERMAL EFFICIENCY



- Premium grade gasoline efficiency is 2-3 three percentage points lower than ethanol blends
- Despite improved efficiency, fuel consumption remains significantly higher for high content ethanol fuels
 - Volumetric energy density of an E85 blend is ~27-30% lower than gasoline, results in large fuel consumption gap with gasoline
 - Volumetric energy density of an E51 blend is ~15% lower than gasoline, results in efficiency comparable to E85 but with reduced fuel consumption gap

CONCLUSION: ALL FUELS COMPLIANT WITH ASTM D5798 OFFER SUBSTANTIAL POTENTIAL FOR ENGINE OPTIMIZATION

- **Refiners and blenders can't help but "give away" octane for ASTM D5798-compliant fuels**
 - E51 blends of C6 and C7 n-paraffins have potential for low RON, but low RVP as well
 - E51 made from straight run gasoline (RON ~65) offers better knock resistance than premium grade gasoline
- **High ethanol fuels enable higher thermodynamic efficiency because they are significantly more resistant to knock**
 - Fuel properties: high chemical octane number and high latent heat of vaporization
 - Engine technologies: higher compression ratio, direct injection, boost, high peak cylinder pressure
- **Octane number of fuel blends is non-linear with vol% ethanol (~constant on molar basis)**
 - About 67% of potential octane number boost is realized with 33 vol% ethanol
 - Engines can be optimized for ethanol with substantially less than 85 vol% ethanol



IN ADDITION TO THERMODYNAMIC EFFICIENCY BENEFITS, ETHANOL OFFERS POTENTIAL FOR SIGNIFICANT SYSTEM EFFICIENCY BENEFITS

- **High level ethanol blends enable higher specific power output**
 - Combined with boost, ethanol allows aggressive downsizing while increasing compression ratio
 - Better low-end torque allows a diesel-like transmission; brake power can be produced more efficiently (down-speeding)
- **Lower exhaust temperature for high ethanol fuel blends can minimize use of enrichment, reducing vehicle fuel consumption**
 - At high loads with high exhaust temperature, engines use fuel-rich operation to cool exhaust in order to protect engine and exhaust system
 - Fuel-rich excursions at 80 mph cruise observed for multiple vehicles at ORNL chassis facility
 - Fuel-rich excursions likely to become more frequent with downsized engines
 - Need for protective enrichment can be substantially reduced with ethanol fuel blends
 - Marginally lower exhaust temperature at comparable combustion phasing for high ethanol blends compared to gasoline
 - Reduced need to retard combustion phasing to mitigate knock, can lead to simultaneous efficiency improvement and exhaust temperature reduction
 - CO emissions for 2007 Saab Biopower were ~8x higher for gasoline than E85 on aggressive US06 cycle (SAE 2007-01-3994)

One Vision of a Fuel Infrastructure/Distribution System for High Ethanol Fuels (talking points, not DOE vision)

- **Ethanol content of high ethanol/high octane fuel would be standardized Exx**
 - 51 vol% ethanol could potentially use existing “E85” ASTM D5798 specification with revision
 - Lower ethanol blend would require new legislation
- **Refiners would continue to produce two high volume products in gasoline boiling range**
 - Exx BOB would have a low octane requirement (RON ~ 70-80), inexpensive for refiners to produce
 - Gasoline or E10 BOB would be premium-grade fuel for total coverage of legacy fleet
 - When BOB volume for Exx is sufficiently high, conceivable that there is no additional cost to refiners or even a profit opportunity
- **Minimal disruption to the ~150,000 U.S. fueling stations and overall distribution system**
 - Majority of fueling stations in the U.S. have 2 underground storage tanks (regular and premium)
 - The two tanks would be converted to a low-ethanol fuel for the legacy fleet and a high octane fuel for newer vehicles
- **OEMs would be able to design higher efficiency engines and vehicle systems**
 - Produce engines and vehicle systems aggressively optimized for Exx (performance and efficiency), necessary to meet CAFE targets
 - Transition to Exx engines would have to occur rapidly and include all OEMs (legislation?)
 - Backward compatibility required for first few years, but dis-incentivized through vehicle performance
 - **Goal would be to approach fuel economy parity with current E10 for consumer acceptance**

Questions?

