# THE IMPACT OF LOW OCTANE HYDROCARBON BLENDING STREAMS ON *"E85"* ENGINE OPTIMIZATION

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DIRECTIONS IN ENGINE-EFFICIENCY AND EMISSIONS RESEARCH CONFERENCE


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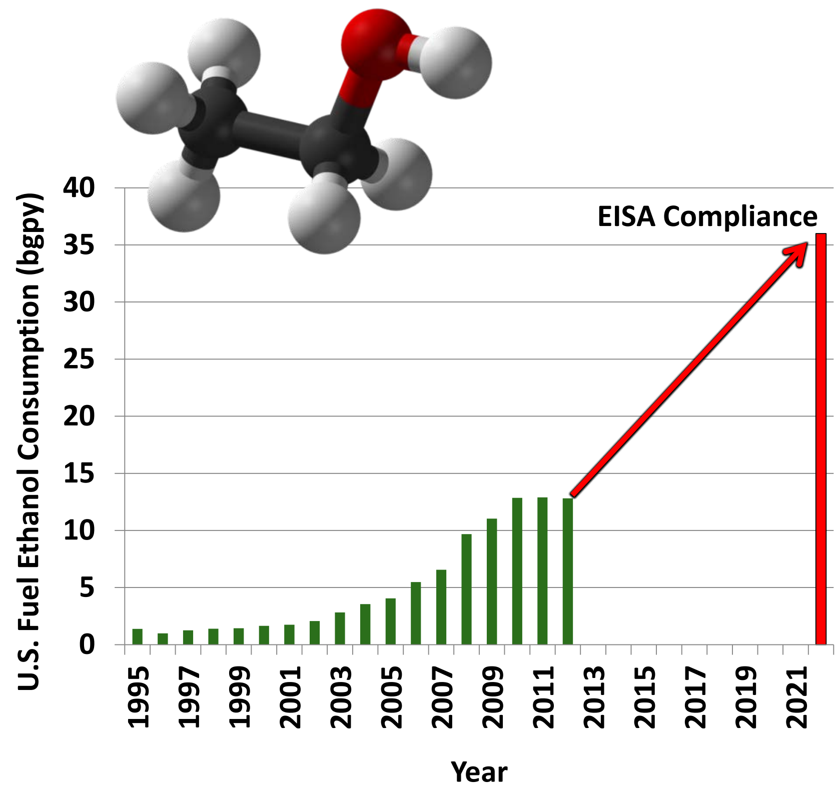
# Ethanol is Currently the Largest Volume Biofuel, Very Important for EISA Compliance

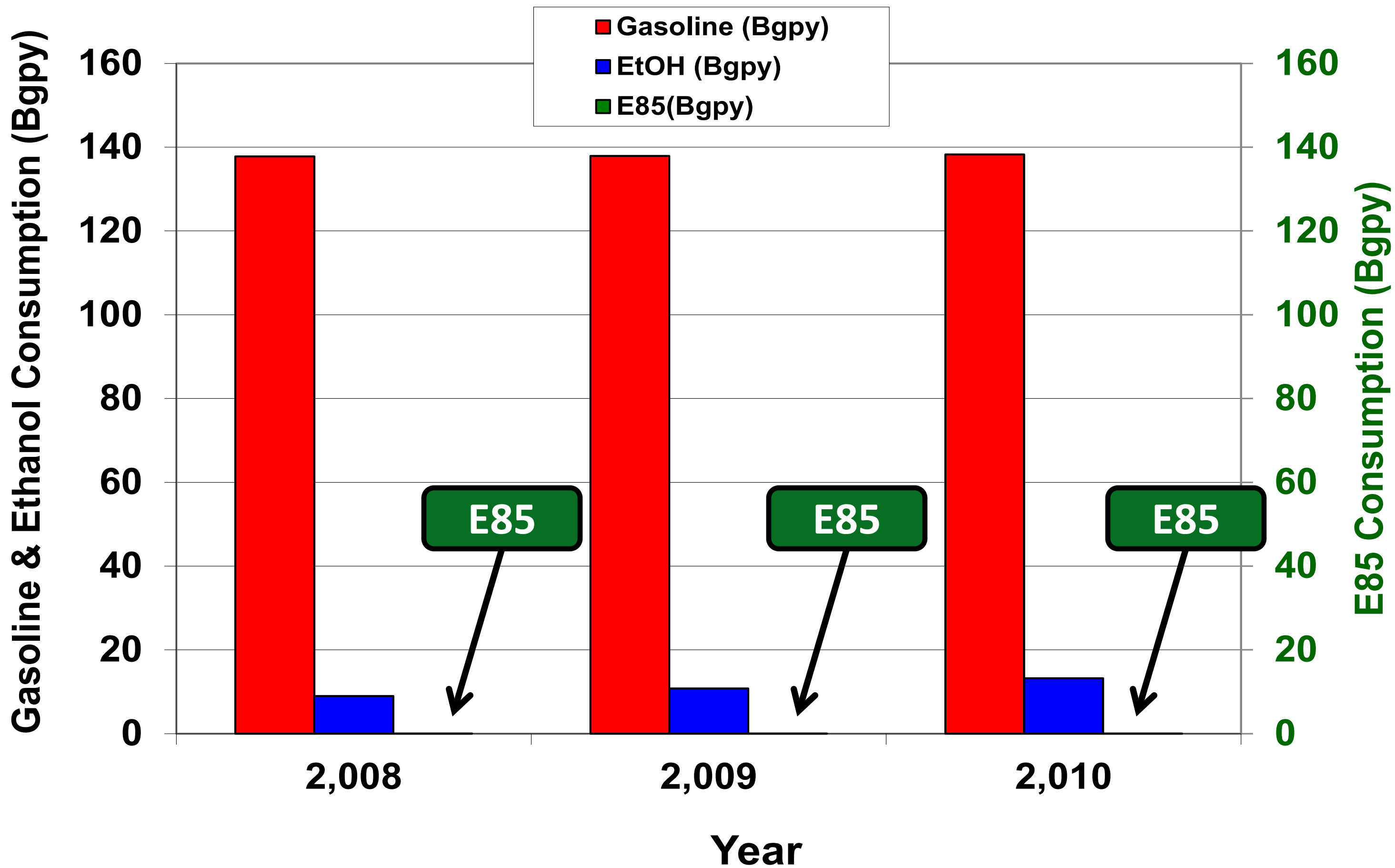
- **Dramatic growth in ethanol use in last 10 years (over 10 billion gallons per year (bgpy))**
- **January 2007 – President launches 20-in-10**
  - Spring 2007 – DOE kicks off intermediate blends studies
- **December 2007 – EISA sets national goals for biofuel use**
  - 36 bgpy by 2022
- **Essentially 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

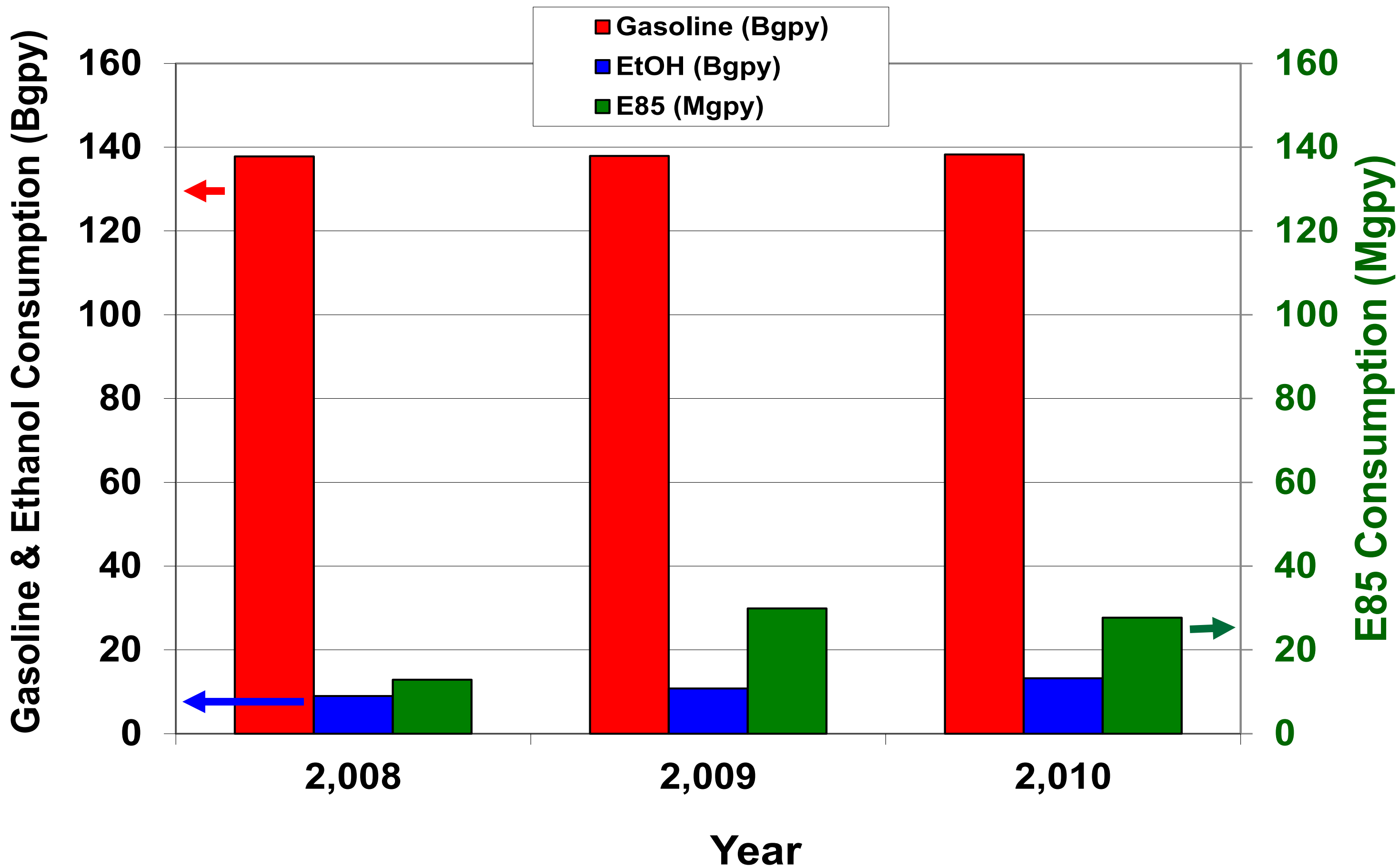
**2012 extrapolated from 6 months of data

# 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




Managed by UT-Battelle
for the U.S. Department of Energy

**Numerous Ethanol Optimization Studies Funded by U.S. DOE**

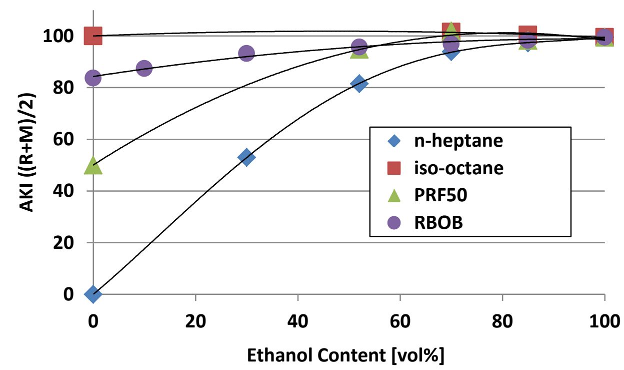
# Changes to ASTM D5798 have possible ramifications on "E85" fuel quality and optimization potential

**Background: 2011 ASTM standard modifies previous specifications for E85**

Designation: D5798 – 11

Standard Specification for
Ethanol Fuel Blends for Flexible-Fuel Automotive Spark-Ignition Engines[1]

- **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



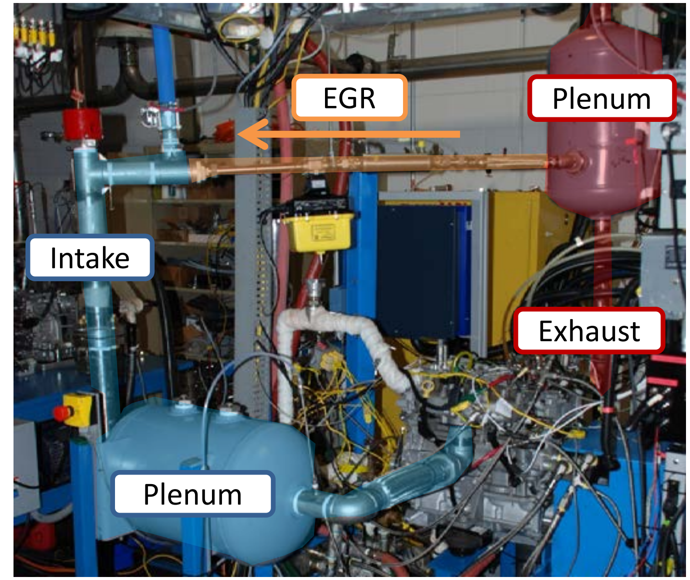

**Results from ORNL blending study showing anti-knock index (AKI) of ethanol blends with different hydrocarbons.**

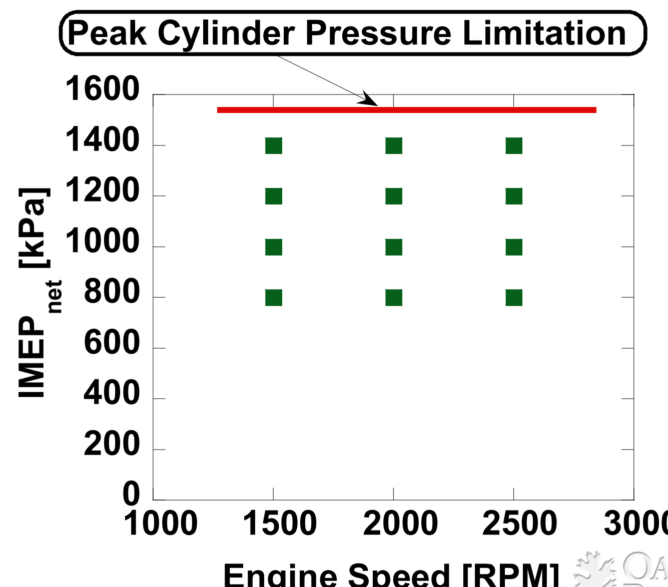
- **Earlier ORNL blending study revealed sufficiently high octane number sufficient for current FFV's**
- **Numerous DOE-funded projects have shown potential for E85-optimized engines**
  - High latent heat of vaporization and octane number are the basis for optimization
  - Engine technologies: direct 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

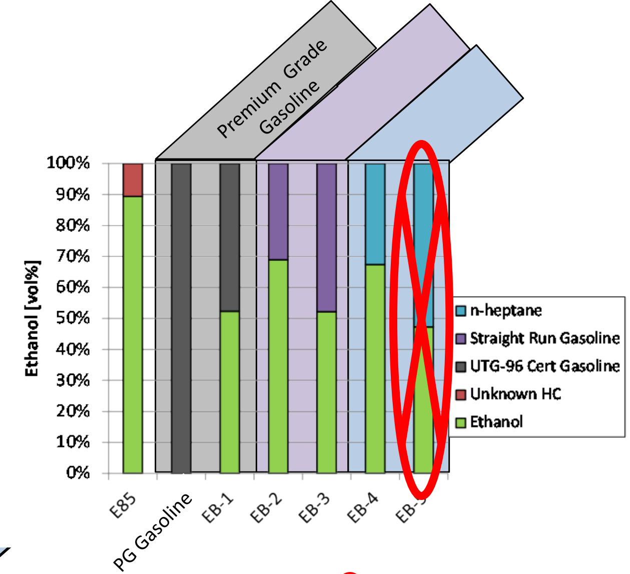
- **Single cylinder engine with hydraulic valve actuation (HVA)**
  - Modified 2.0L GM Ecotec engine (bore x stroke = 86mm x 86 mm)
  - High compression ratio (12.9:1), direct injection fueling, boost
  - DRIVVEN controller for engine management
- **Knock-prone operating conditions**
  - Low speed (1500 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



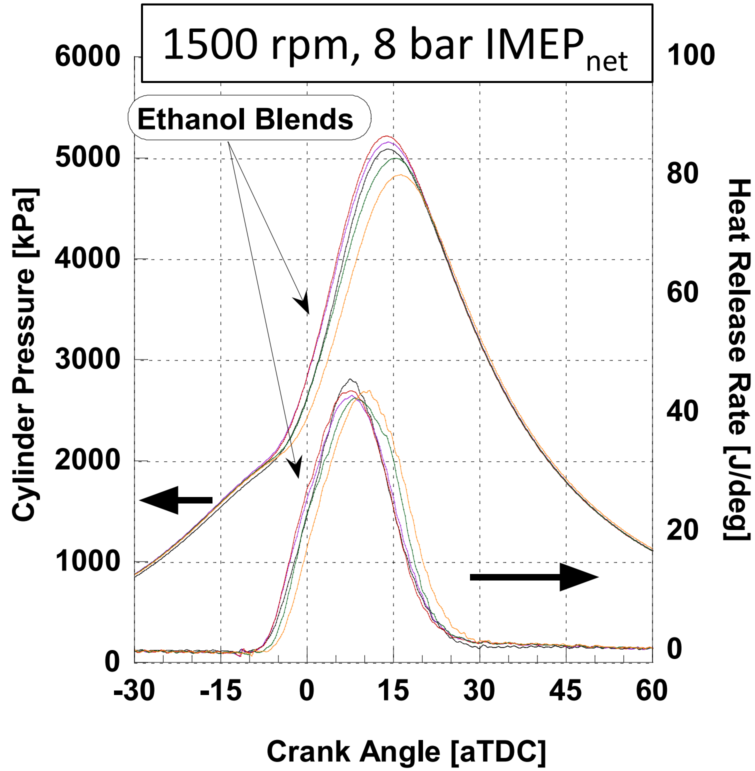
# Hydrocarbon Streams with Wide Range of Octane Number Blended with Ethanol

- **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




| | Spec. | Premium Gasoline | E85 | EB-1 | EB-2 | EB-3 | EB-4 | EB-5 |
|---|---|---|---|---|---|---|---|---|
| Hydrocarbon Type | | 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.[illegible]2 |
| Hydrogen wt/% | ASTM D5291 | 13.2 | 12.92 | 13.10 | 13.78 | 14.28 | 13.92 | 14.48 |
| Specific Gravity | ASTM D4052 | .739 | .788 | .768 | .753 | .732 | .756 | .7[illegible]8 |
| Octane nr (R+M)/2 | N/A | 92.2 | 96.9 | 97.5 | 96.5 | 95.0 | 93.3 | [illegible].2 |
| Research Octane Number | ASTM D2699 | 96.1 | 105.0 | 104.4 | 104.1 | 102.0 | 100.4 | 8[illegible]4.8 |
| Motor Octane Number | ASTM D2700 | 88.2 | 88.7 | 90.5 | 88.9 | 88.0 | 86.2 | 7[illegible].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 | 31.608 | 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 | | 35.0 | 41.1 | 40.6 | 70.6 | 70.6 |
| 10% Distillation [°C] | ASTM D86 | 50.0 | | 57.2 | 55.0 | 50.6 | 71.1 | 71.[illegible] |
| 50% Distillation [°C] | ASTM D86 | 107.2 | | 76.7 | 76.7 | 67.8 | 73.3 | 71.[illegible] |
| 90% Distillation [°C] | ASTM D86 | 150.0 | | 89.4 | 77.8 | 77.8 | 77.8 | 76.1 |
| Final Boiling Point [°C] | ASTM D86 | 185.0 | | 168.3 | 78.9 | 78.9 | 77.8 | 78.3 |

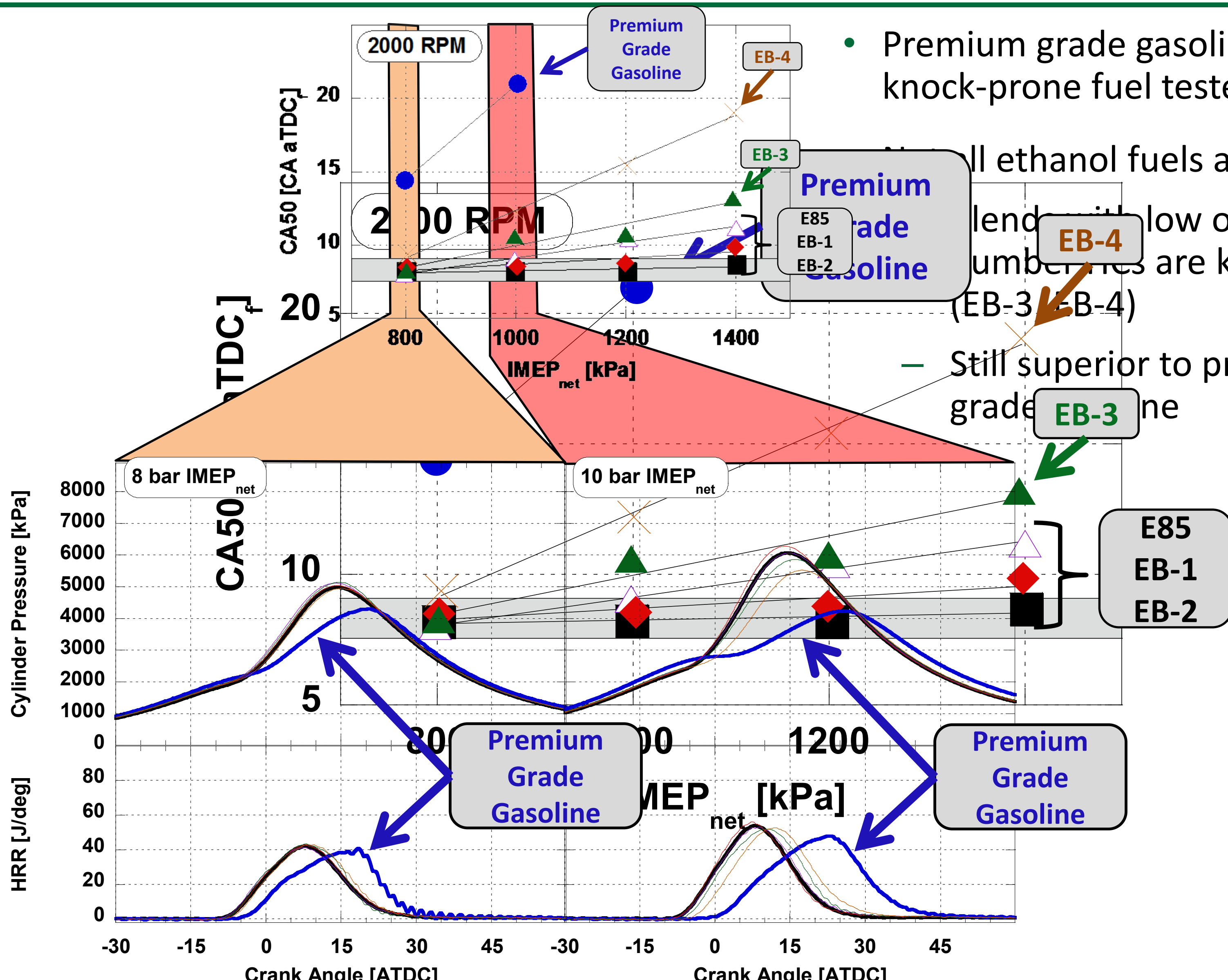
# All Ethanol Fuel Blends Exhibit Superior Knock Resistance Relative to Premium Grade Gasoline



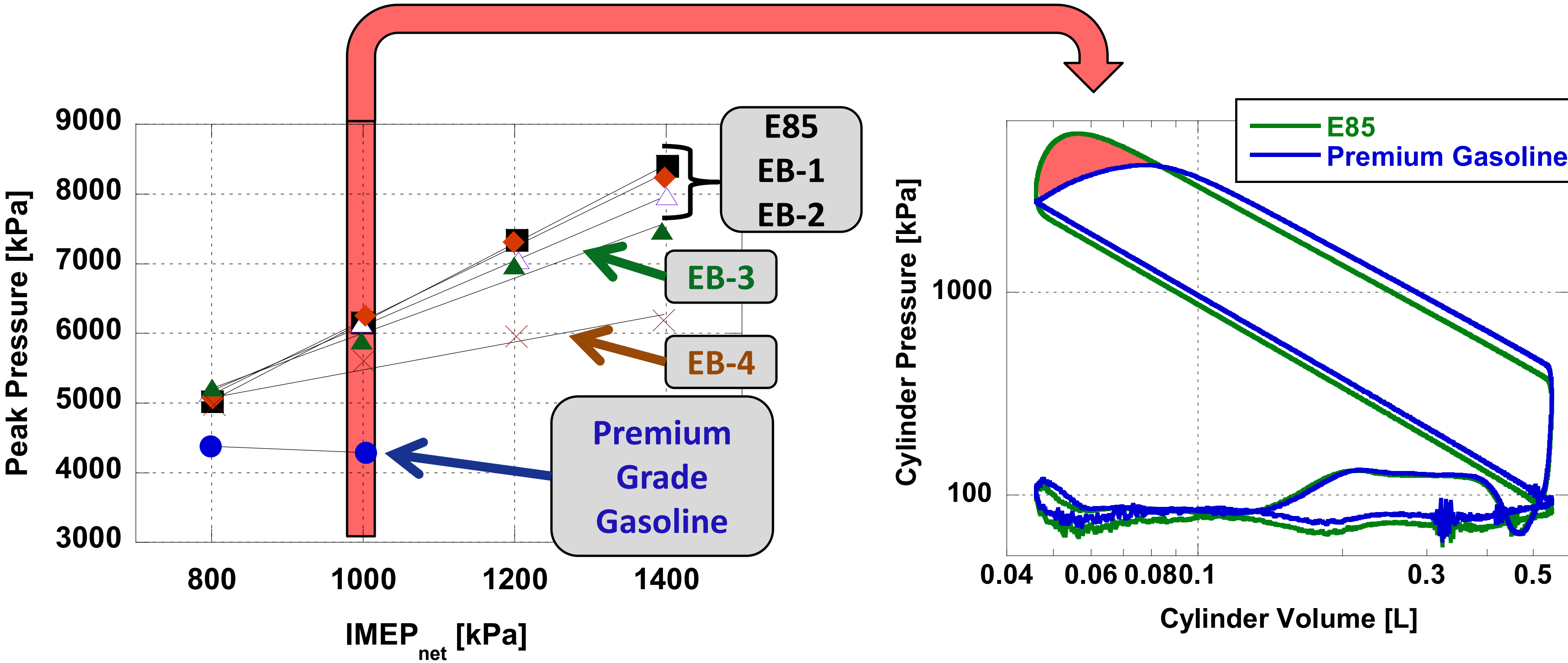

**Spark timing used to retard combustion phasing for knock mitigation**

# Premium-Grade Gasoline has the Most Retarded Knock-Limited Combustion Phasing

- Premium grade gasoline is most knock-prone fuel tested
- …ll ethanol fuels are the same
  - …lend… low octane …umber… are knock-limited (EB-3 …EB-4)
  - Still superior to premium grade… ne

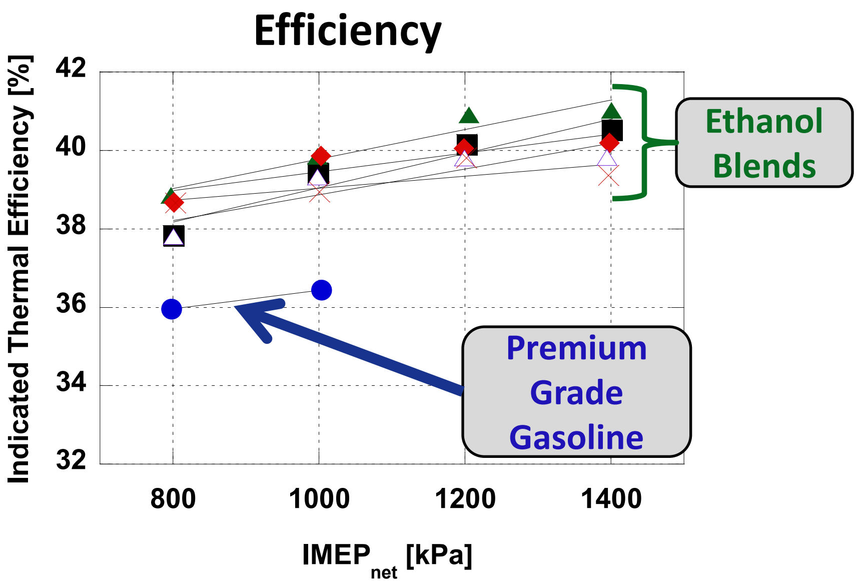


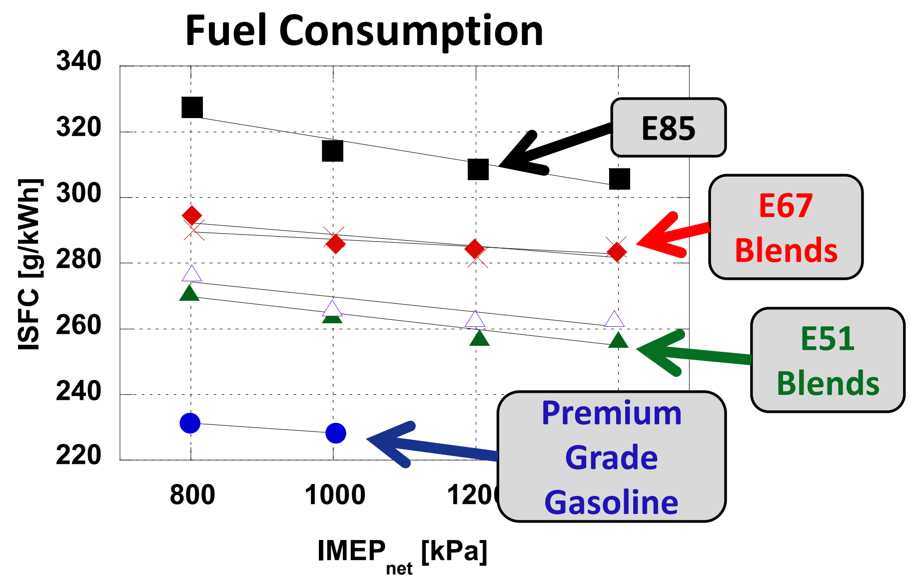
# Retarded Combustion Phasing Decreases Peak Cylinder Pressure and Incurs an Efficiency Penalty




- **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

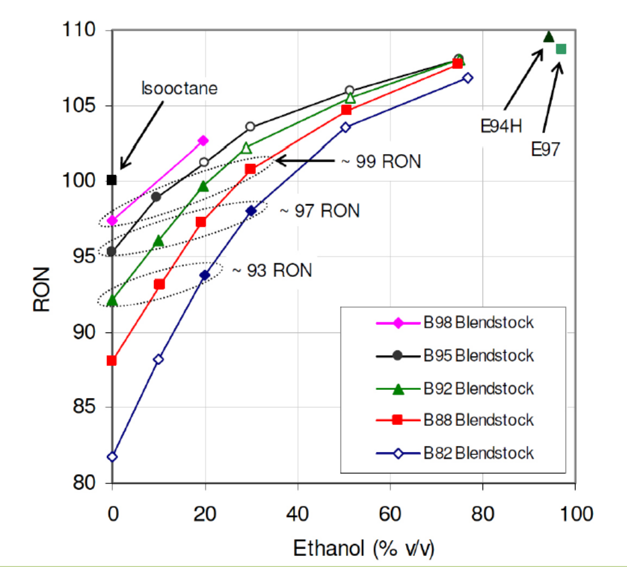



- **Premium grade gasoline efficiency is 2-3 three percentage points lower than ethanol blends**
- **Despite improved efficiency, fuel consumption remains significantly higher for high content ethanol fuels**
  - Volumetric energy density of an E85 blend is ~27-30% lower than gasoline, results in large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




*Stein et al/ SAE Int. J. Fuels Lubr./Volume 5, Issue 2 (May 2012), SAE 2012-01-1277*

# 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?