# Methods of reducing transportation energy and petroleum consumption and environmental impacts.


## A discussion of internal combustion engine fundamentals, efficiency sources, and fuel-related powertrain opportunities.

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**Acknowledgement**
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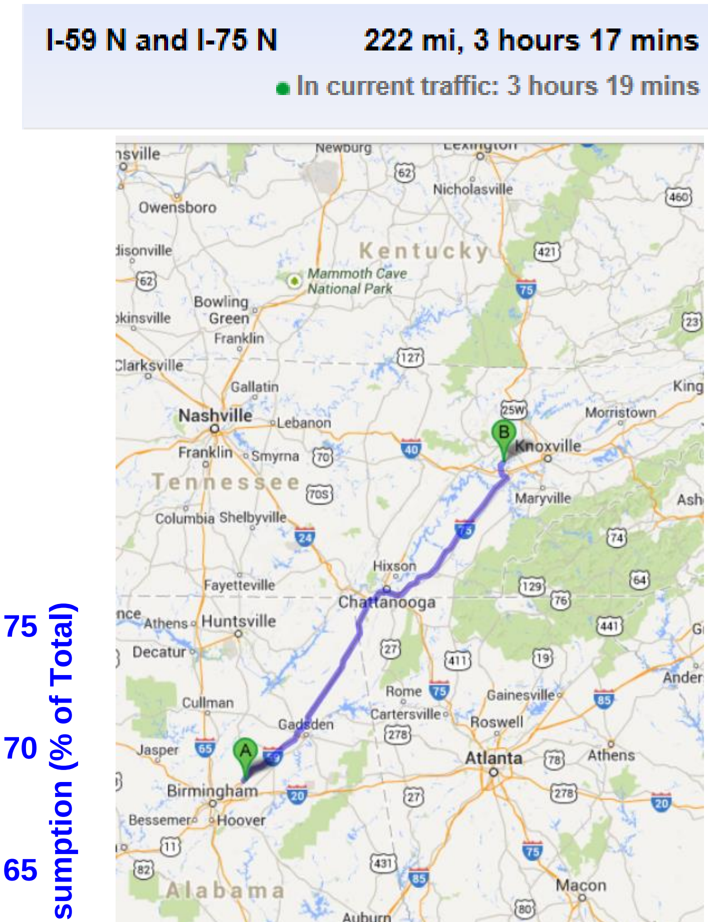
# TRANSPORTATION CONSUMPTION AND REDUCTION LEGISLATION

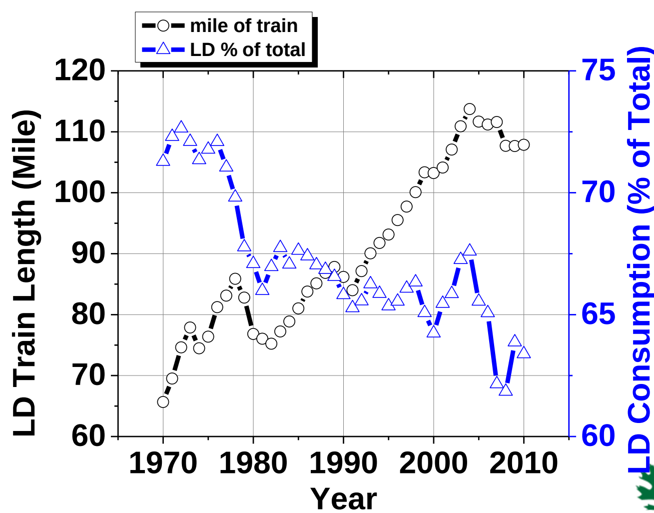
- **LD Transportation Consumes Petroleum** [1]
  - **2011 LD Hwy transportation $= 17.4 * 10^{15}$ BTU**
    - **Equivalent to**  *** 8,215,000 per Day!**

**Or**  *** 26,291** [2, 3]




    - **≈+222 Mile long train PER DAY!**
    - **ORNL to ~ Birmingham, AL** [4]

- **LD & Total consumption increasing** [5]
  - **In 2011 NHSTA legislation passed**
  - **2 fold increase in corporate average fuel economy (CAFE) standards**
  - **54.5 U.S. miles/gal by 2025**
  - **Cars 99% gasoline**

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# Methodology to Reduce Fuel Consumption

- Fundamentally what is going on in internal combustion engines
- What do we need to be concerned about in terms of efficiency?

- Engine combustion processes
- In-application high octane bio-fuel results
- High octane fuels are powertrain configuration and efficiency enablers

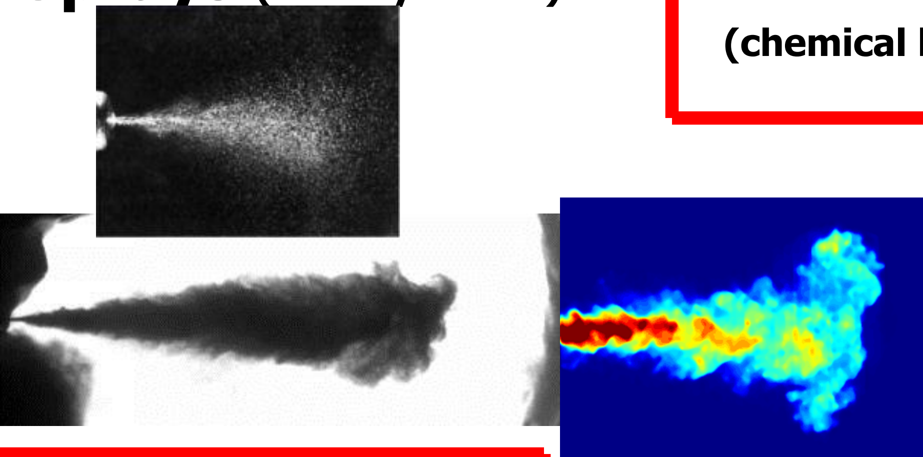
- Alternative combustion processes (LTC)
- LTC efficiency paradox
- Gross to brake efficiency challenges

**"The engine is the ideal teaching tool – it features all of the elements of engineering: materials, fluids, thermodynamics, lubrication, chemistry, electronics, etc. The only thing missing is nuclear reaction."**

***-Phil Myers***

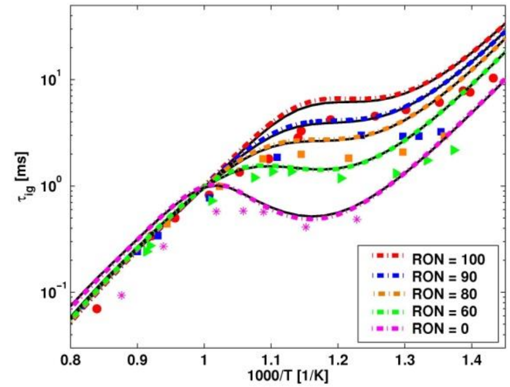
# Engine Research Areas

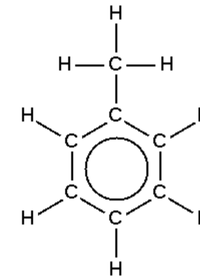
## Sprays (fluid dynamics)

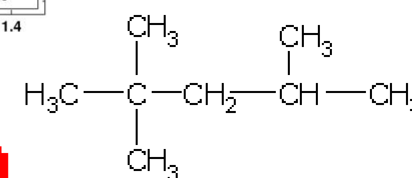


## Fuel Chemistry

(chemical kinetics, organic chemistry)



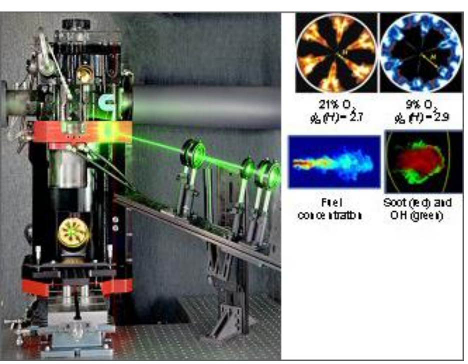



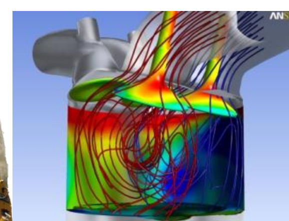


iso-octane (2,2,4-trimethylpentane)
Octane number assumed to be 100

## Combustion

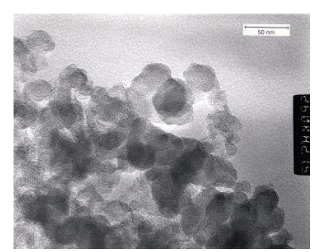
(thermodynamics, fluid dynamics, heat transfer)

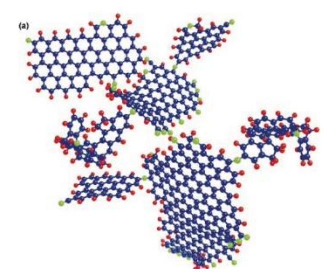




## Emissions

(particle dynamics, chemistry)





# Combustion Fundamentals

- Fundamentally what is going in on internal combustion engines
- What do we need to be concerned about in terms of efficiency?

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- LTC efficiency paradox
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# How Efficiently Can I Get Work Out of My Engine?

- **Internal Combustion Engines are NOT a thermodynamic cycle!**
  - **Not governed by Carnot Efficiency!**
- **Engine is a chemical reaction constrained to a changing volume to convert chemical potential to work**
  - **new working fluid every fired cycle + working fluid changes composition!**

**Max work from fuel**

$$W_{max,useful} = -\Delta G_{T_o,P_o}$$

**Max work from device**

$$\eta_{thermal} = 1 - \left(\frac{1}{r_c^{(\gamma-1)}}\right)$$

- **Efficiency is dependent on amount work ($W_{max,useful}$) and how well work is extracted in the cycle**
  - **Engine efficiency couples chemical reaction to the device**

# Maximum Work Cares About Temperature and Composition

Δcomposition — Surroundings — Δ Irreversibility

$$W_{max,useful} = -\left(H_p - H_r\right) + T_o\left(S_p - S_r\right)$$

$$h = \sum n_i\left(\bar{h}^o{}_f + \Delta\bar{h}\right)_i$$

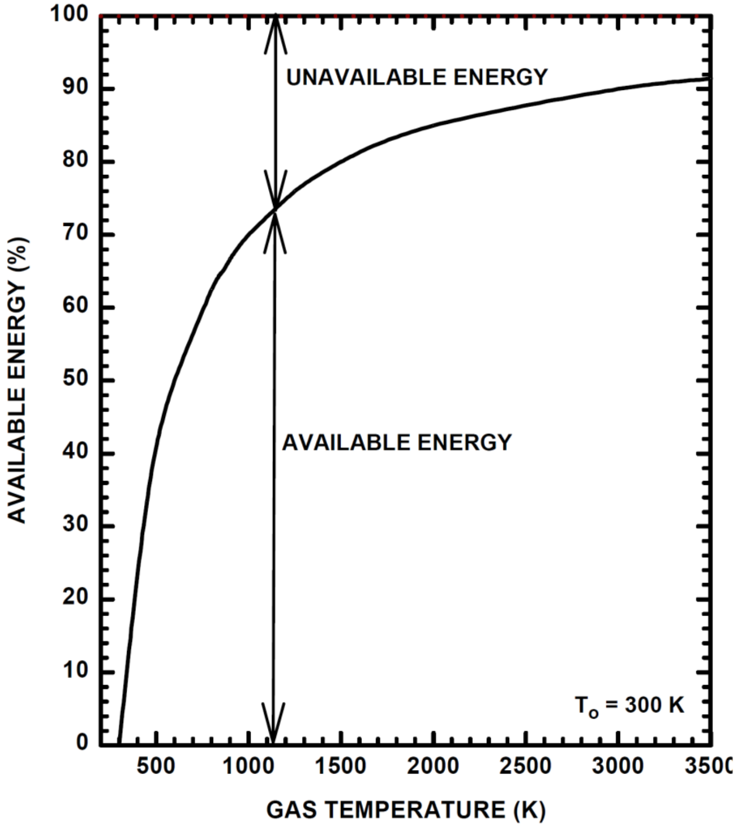
For an ideal gas $h = c_p * T$

For an ideal gas $\Delta s = c_p ln\frac{T_2}{T_1} + R ln\frac{p_2}{p_1}$

$$W_{max,useful} \propto T$$

- work available from fuel is directly dependent on T
- High temperature affects engine operation and lowers eff.
  - Heat transfer and γ

[6]



# In-practice Combustion Processes and Fuel Property Efficiency Enablers

- Fundamentally what is going in on internal combustion engines
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- **Engine combustion processes**
- **In-application high octane bio-fuel results**
- **High octane fuels are powertrain configuration and efficiency enablers**

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- LTC efficiency paradox
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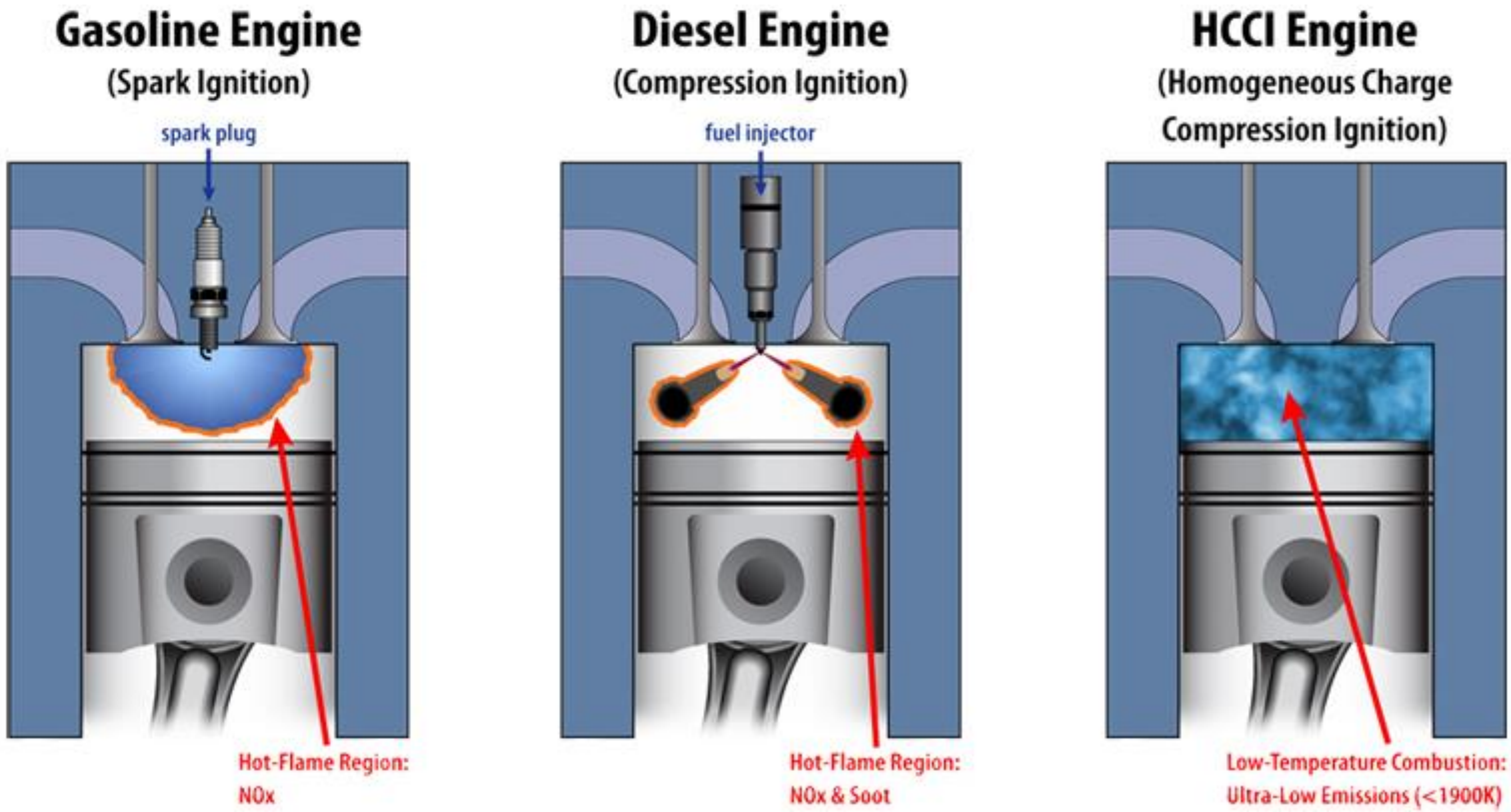
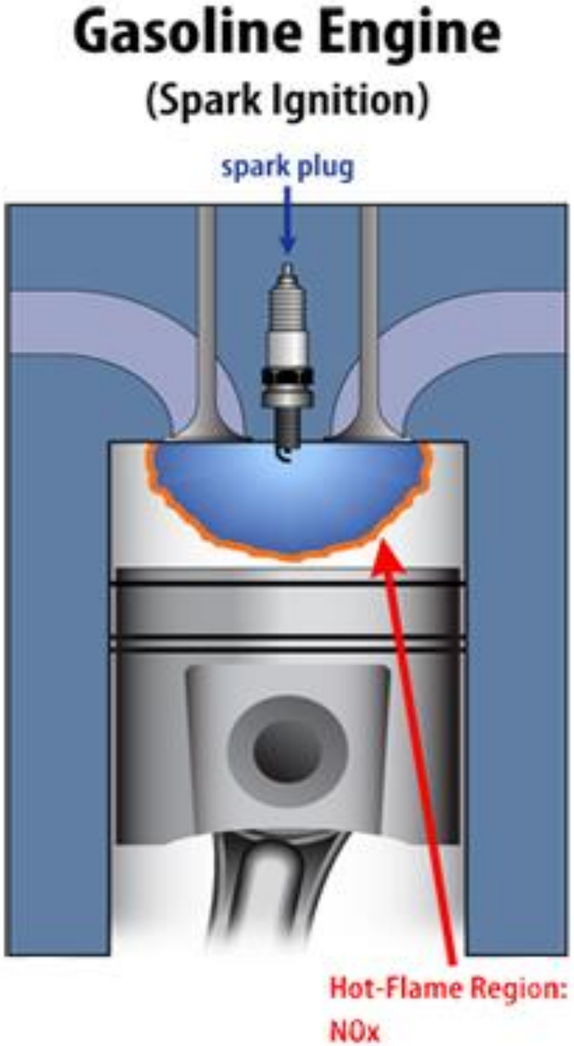
# What Forms of Combustion are Used?



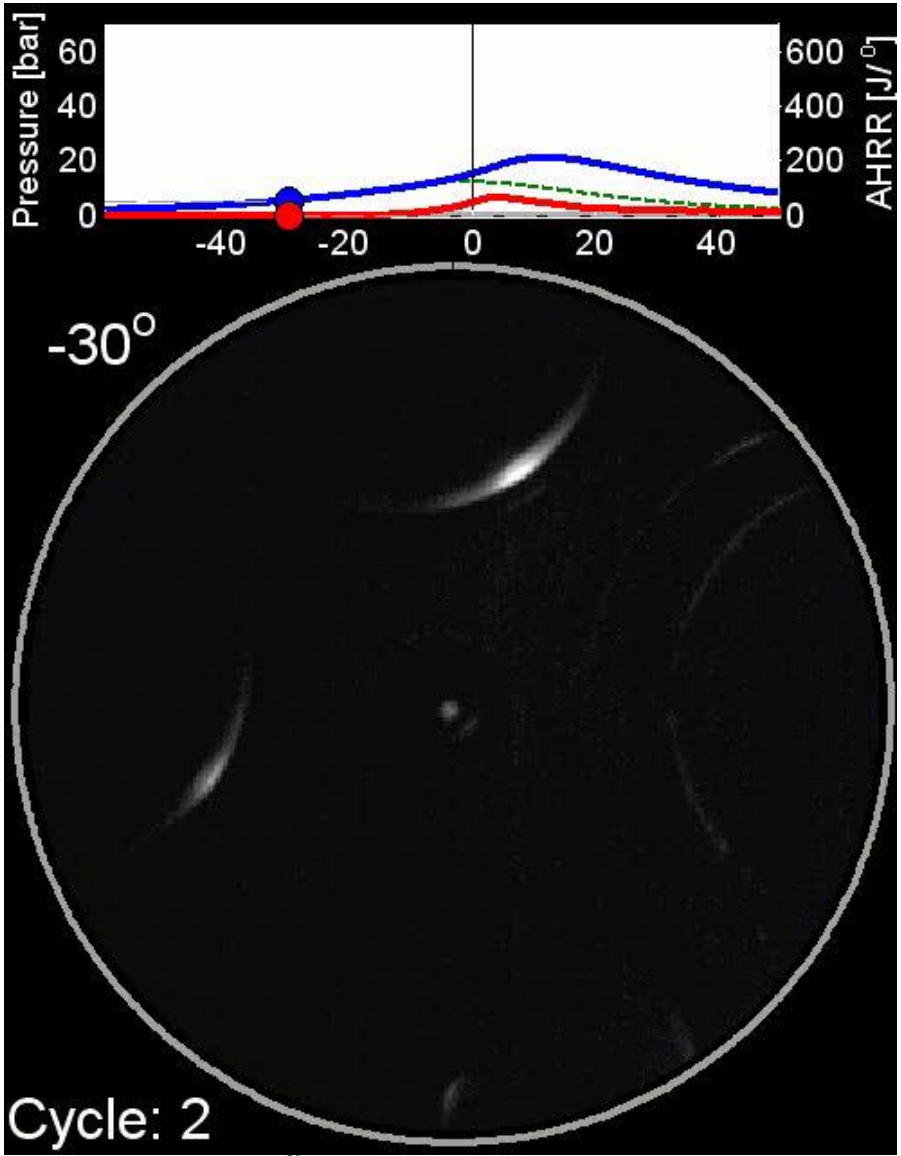

**Flame propagation** **Mixing controlled** **Autoignition**

[Images adopted from 21]

# Flame Propagation (gasoline)

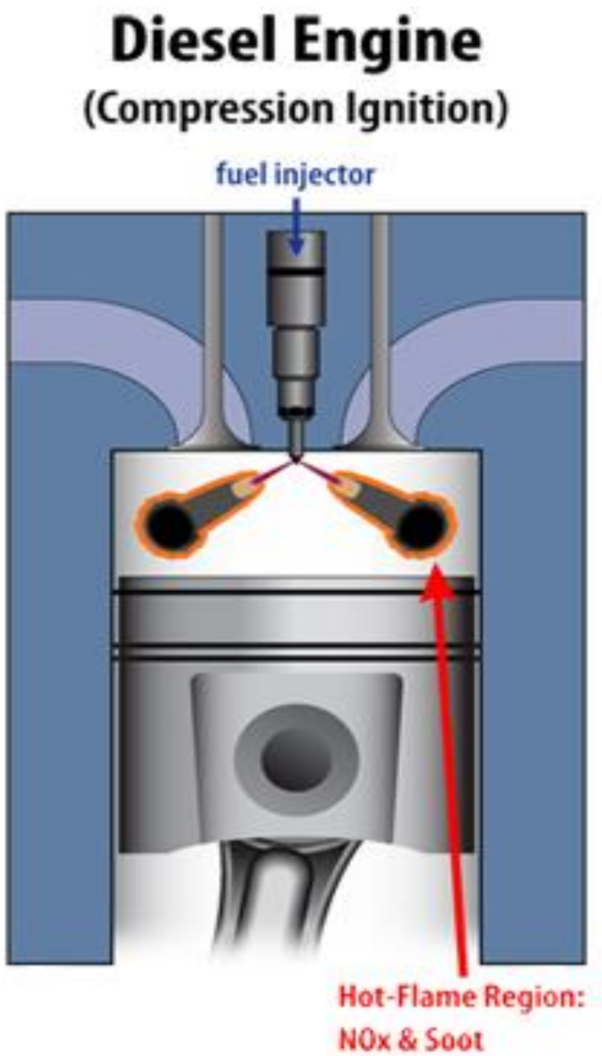


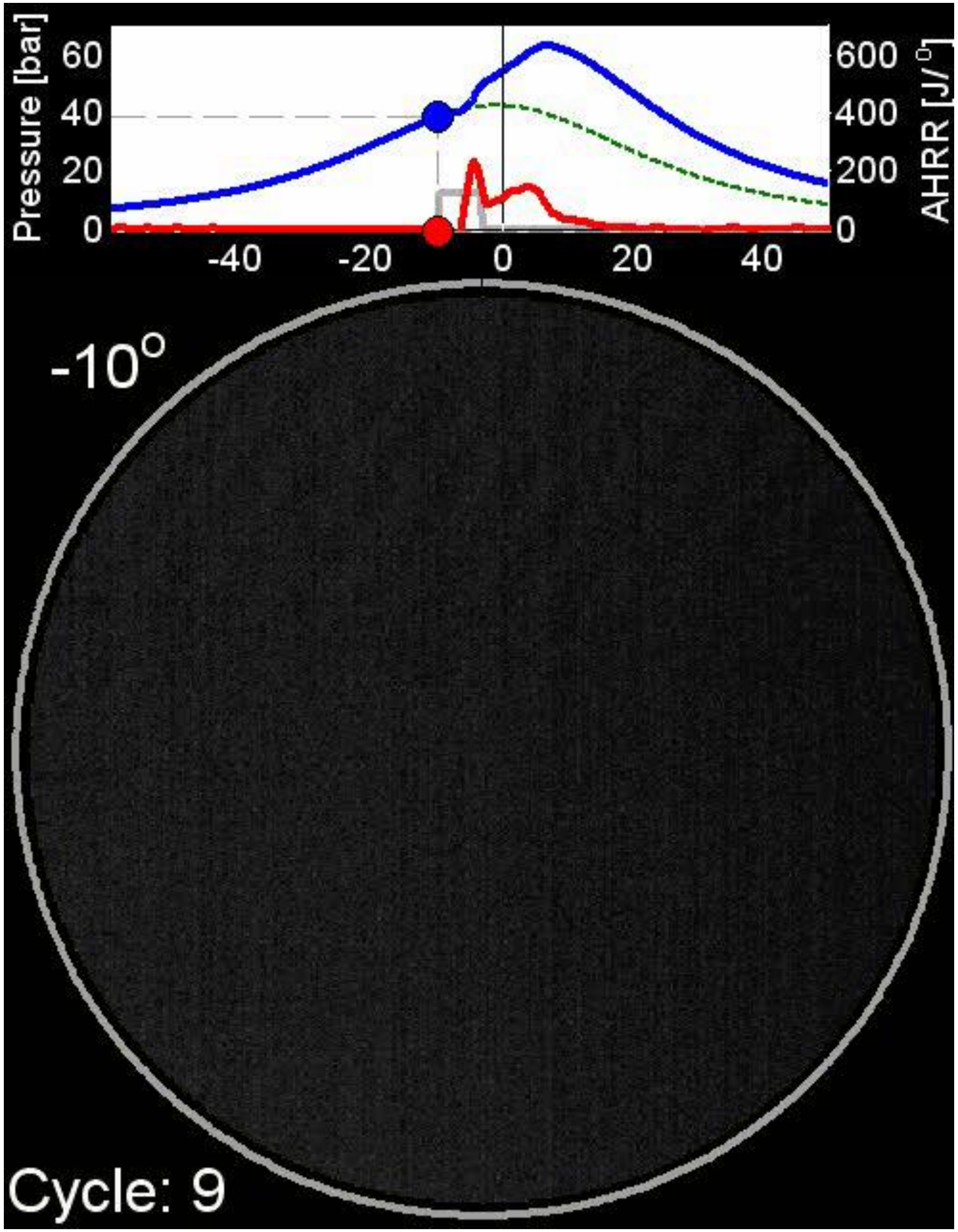

**Easy to control**
**Command Spark**




Video courtesy of Sage Kokjohn, UW Madison

# Mixing Controlled (diesel)

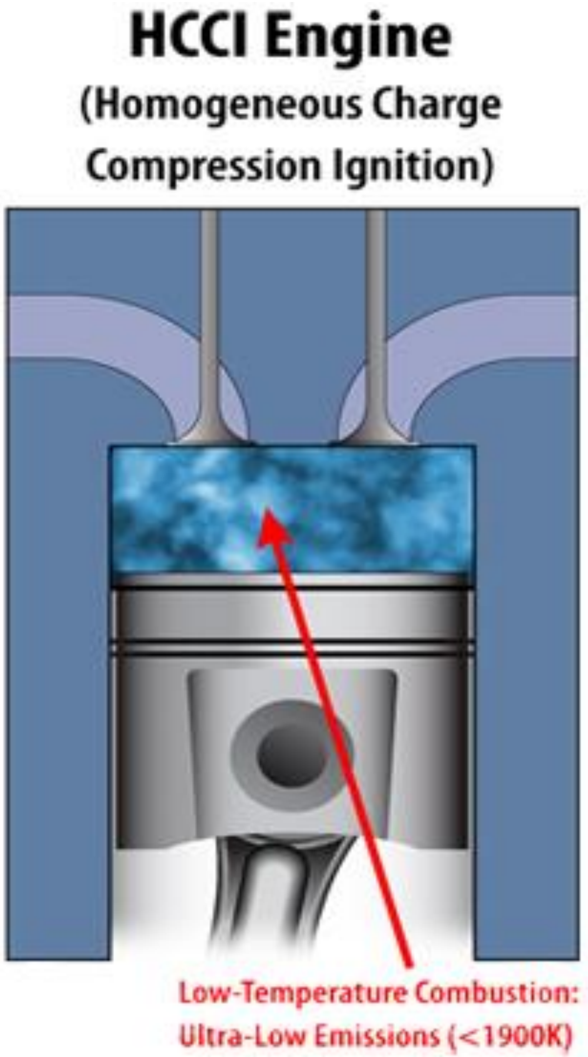


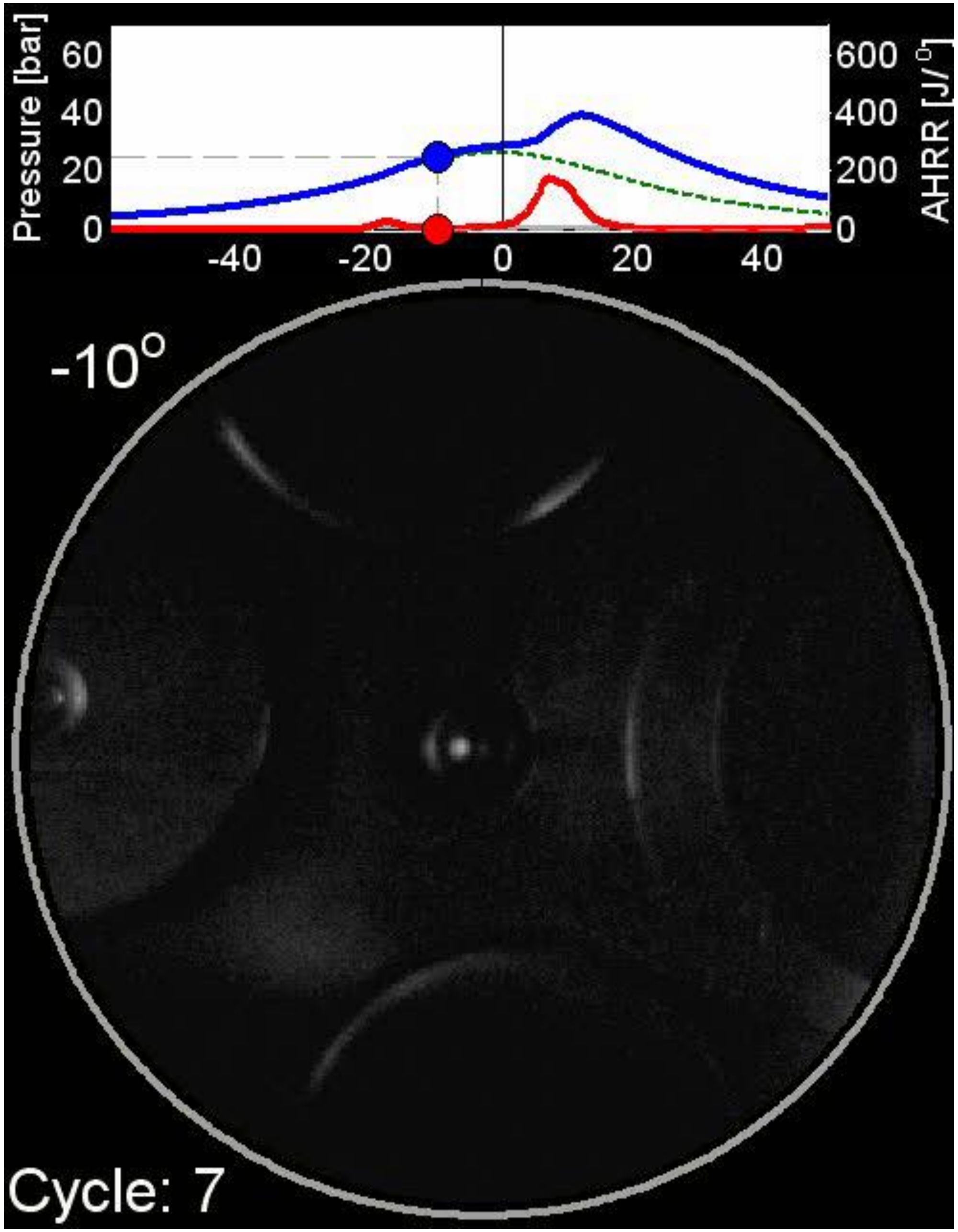




**Easy to control**
**Command Spray**

Video courtesy of Sage Kokjohn, UW Madison

# Bulk Autoignition (HCCI)



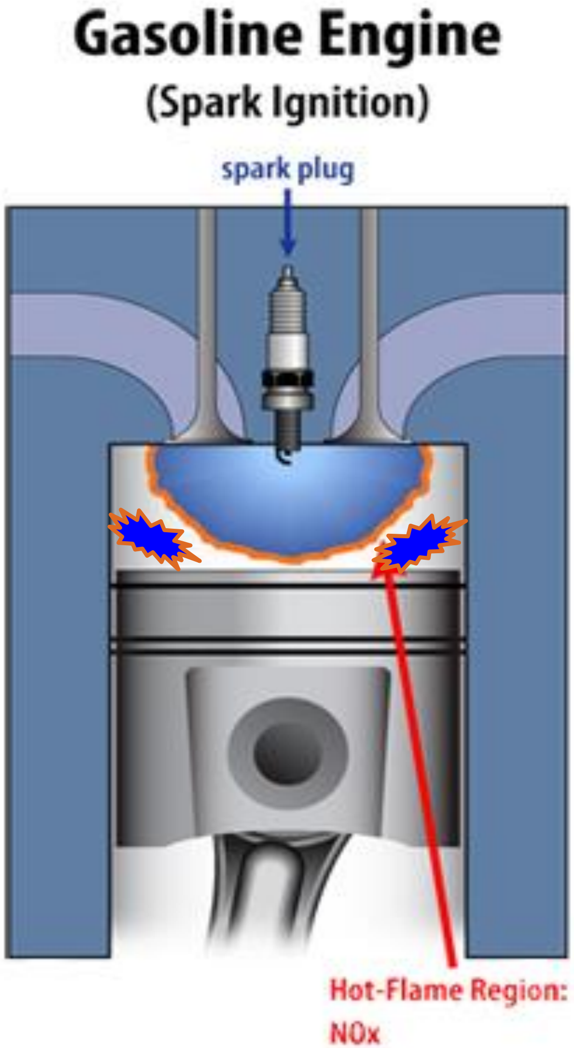




**Difficult to control**

**is fuel specific**

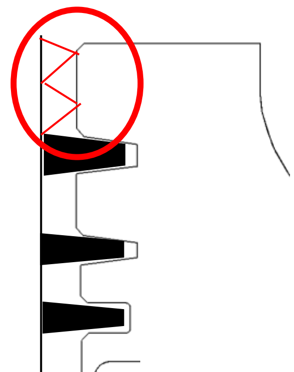
Video courtesy of Sage Kokjohn, UW Madison

# Knock Limits SI Engine Efficiency




$$autoignition_{time} = Ae^{\left(\frac{E_a}{RT}\right)}$$

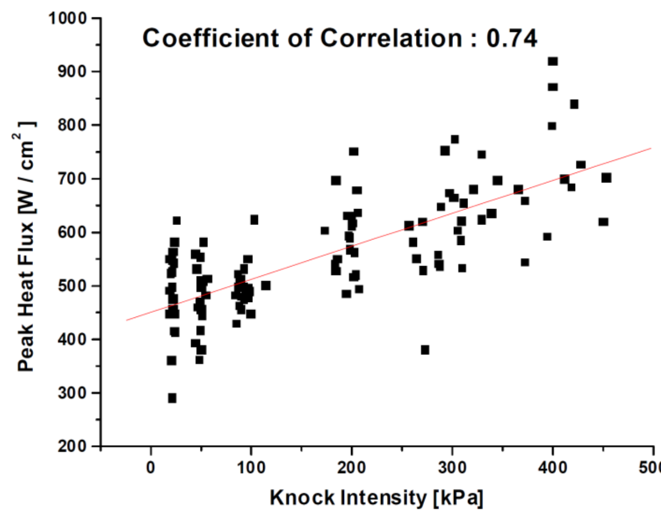
- **Knock can create oblique shocks**
  - Shock compression down ringland
  - $P_{local}$ > material yield



**Knock sets compression ratio ($r_c$) (i.e., cycle efficiency)**

$$\eta_{thermal} = 1 - \left(\frac{1}{r_c^{(\gamma-1)}}\right)$$

- **Knock increases heat transfer**



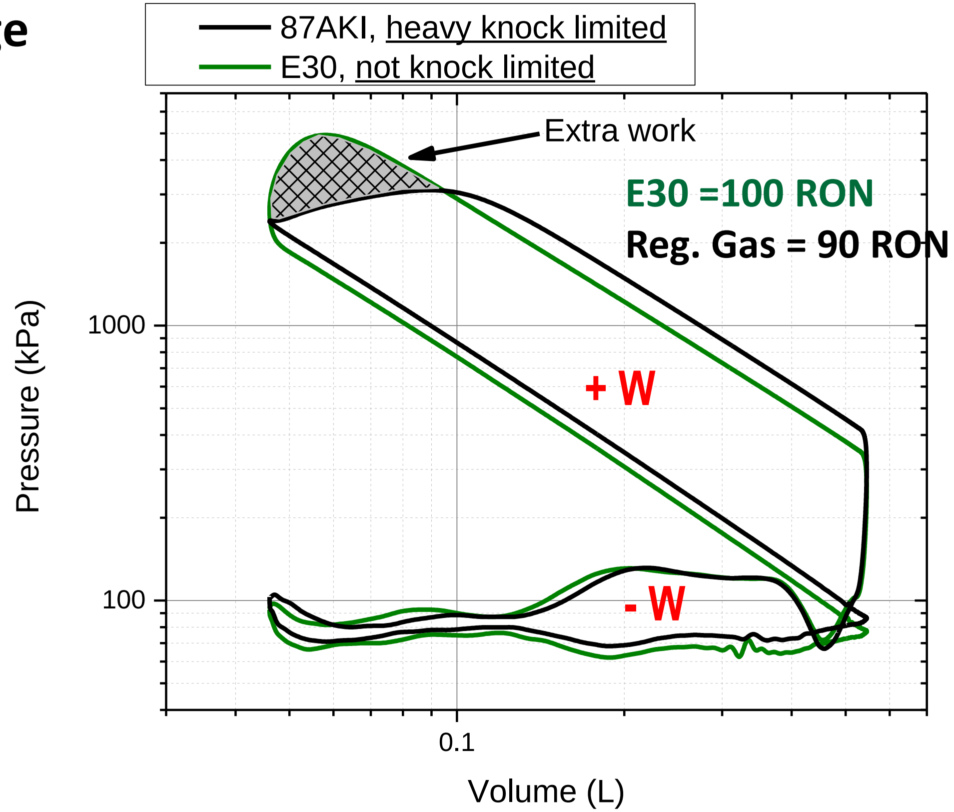

http://www.youtube.com/watch?feature=player_detailpage&list=PL01EEAE444A42515D&v=kAVnMlwbGqE#t=436 [8]

# Lower Octane Number Reduces Maximum Load and Increases High-Load Fuel Consumption

- **To avoid knock combustion phasing is retarded** → $autoignition_{time} = Ae^{\left(\frac{E_a}{RT}\right)}$
  - **During combustion unburned charge**
    $$PV = nRT$$
- **Couple chemical reaction ( i.e., $W_{max,useful}$) to the engine cycle**

$$W = \int P\, dv$$

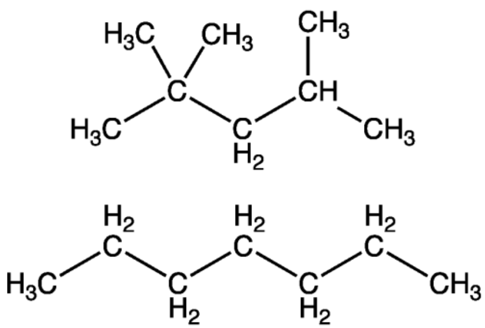
- **Want most P and DV**
- **Knock avoidance reduces efficiency**

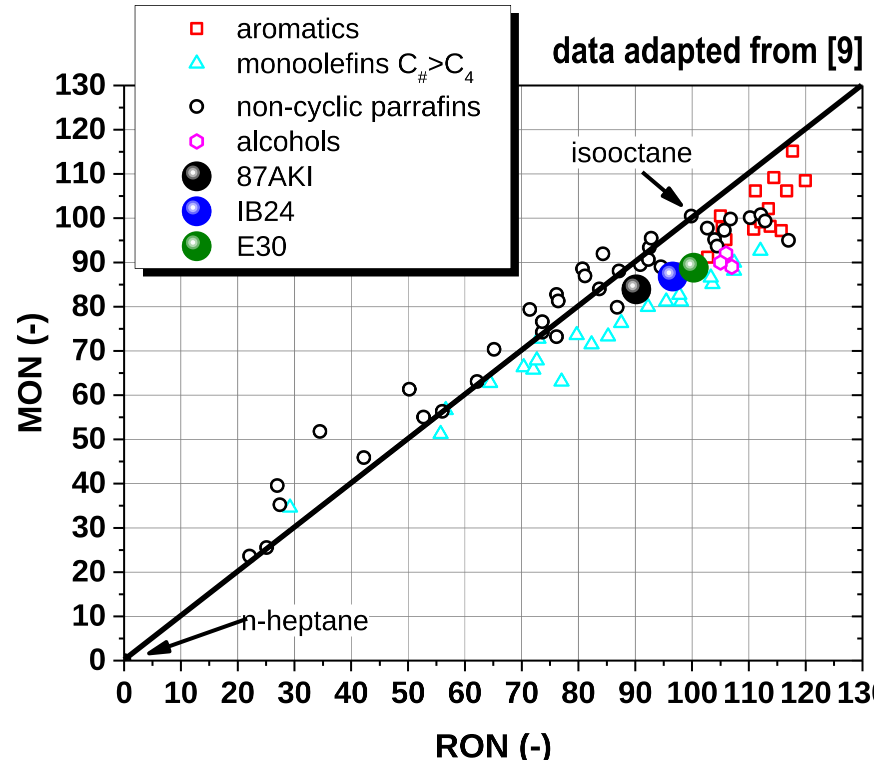



**Propensity to knock is reduced with higher octane number**

# Octane Number is a Rating Relative to a Reference

- **Octane scale defined long ago…**




- **Octane number factors**
  - bonds, statistics, conditions, etc…
- **Correlate real fuels to reference**
  - Non-cycle paraffin define scale
    - These are highly sensitive to pressure!

- **Octane number tells only part of the story**
- **Referenced to normal paraffin**

# High Octane Fuels already on market…

## Consumers are not choosing E85 when it is available

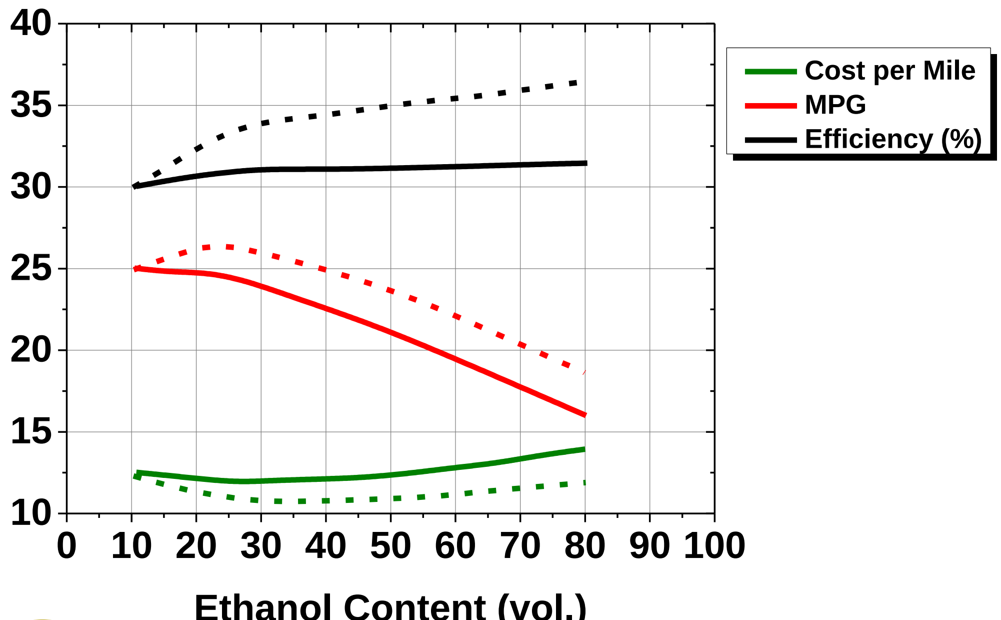
- More than 14 million FFVs on the road
- Ave. FFV less than 4 gal. E85 per year!


## Is a "*Renewable Super Premium*" a Better Path for Ethanol?

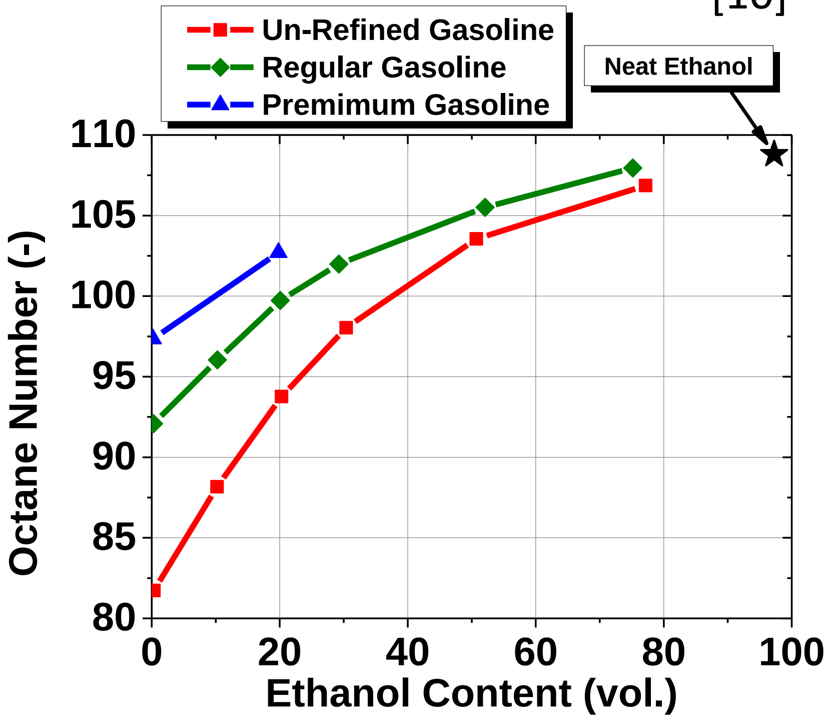
- It is likely that optimum blend is E20-E40

Solid = FFV

Dashed = EtOH optimized engine




[10]

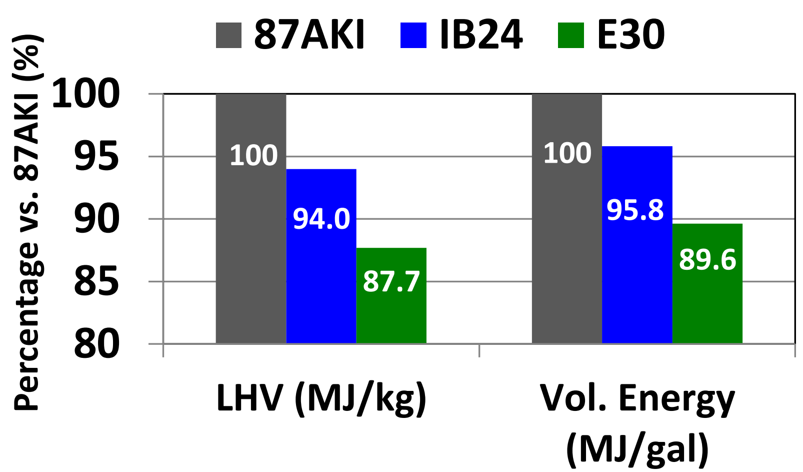


# Recent High Octane SI Bio-Fuel work at ORNL Shows Optimization in Efficiency and Fuel Energy

- 3 Fuels Tested
  - 87 AKI
    - "regular" pump gasoline, 0% EtOH
  - IB24
    - 87 AKI + 24% Iso-butanol (vol./vol.)
  - E30 (renewable super premium)
    - 87 AKI + 30% Ethanol (vol./vol.)

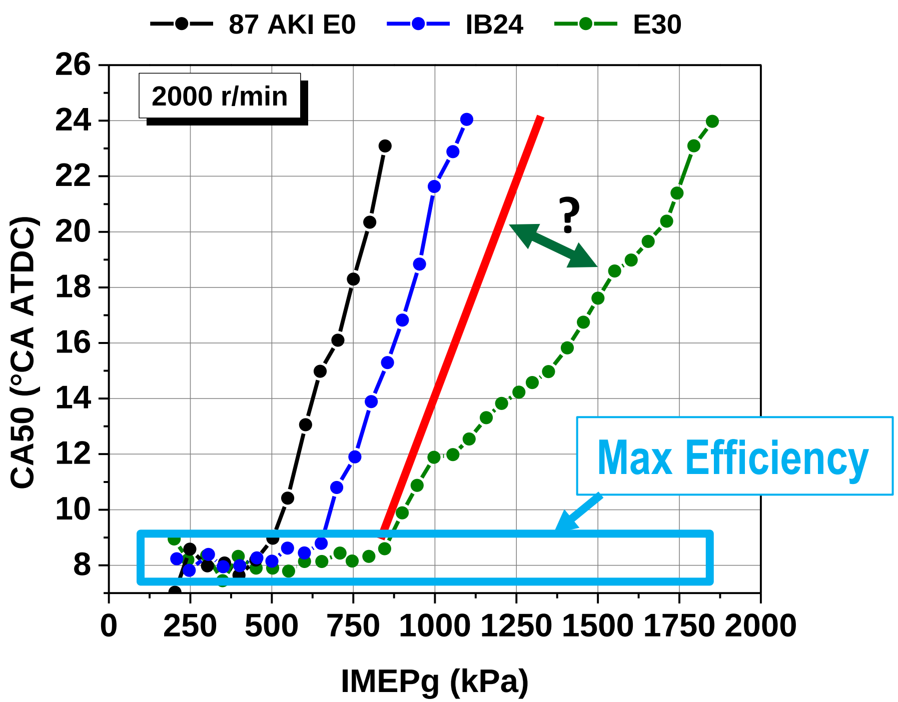
| | 87 AKI | IB24 | E30 |
|---|---|---|---|
| RON (-) | 90.2 | 96.6 | 100.3 |
| MON (-) | 83.9 | 86.8 | 88.8 |
| S (-) | 6.3 | 9.8 | 11.5 |

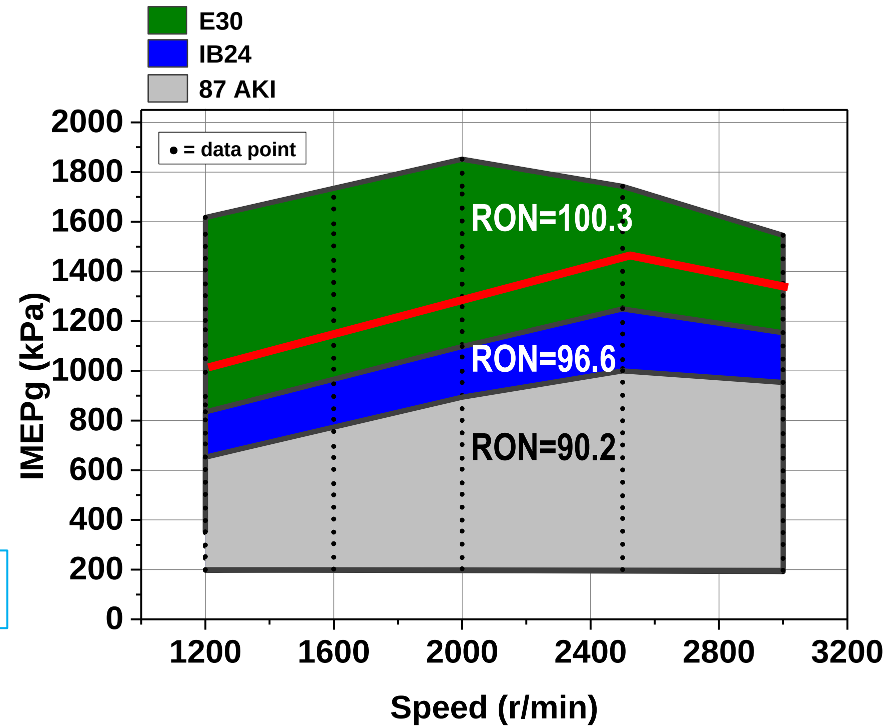
- FFV customer w/E30
  - ~12% MPG reduction
- Engine must capitalize on other fuel properties to offset ethanol energy deficit

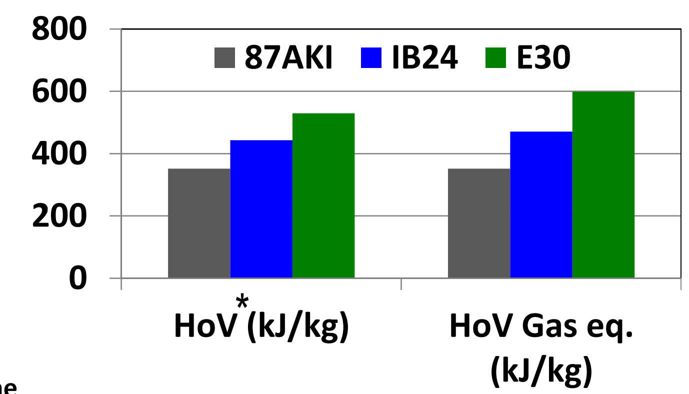


# E30 Benefits are Beyond Octane Number…….

- **Knock limits SI Engine Load & η**




**E30 Benefits are Beyond AKI**

*API Pub. 4261, June 2001

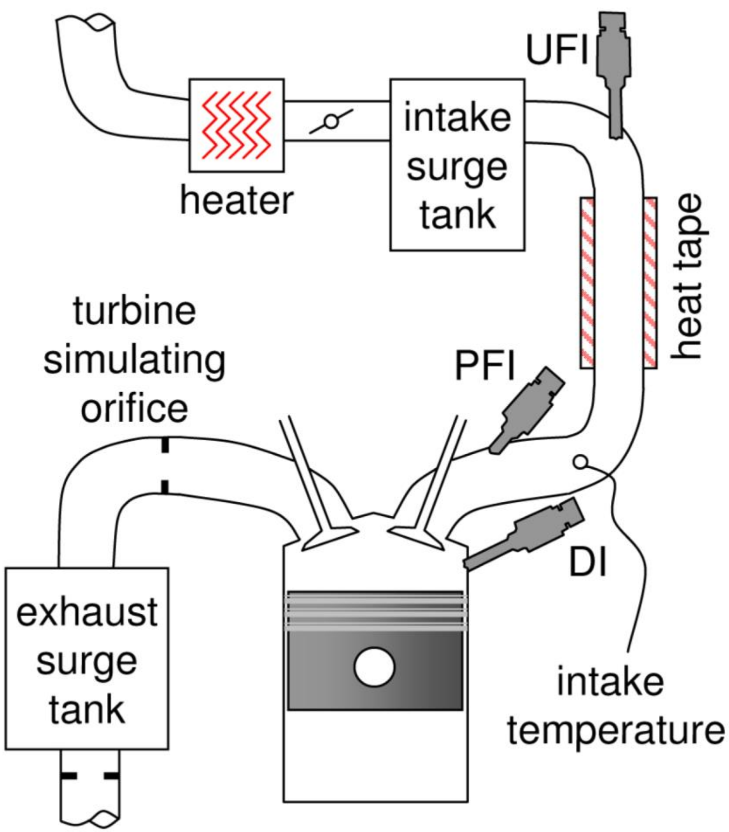
*NREL, "Utilization of Renewable Oxygenates as Gasoline Blending Components", 2011

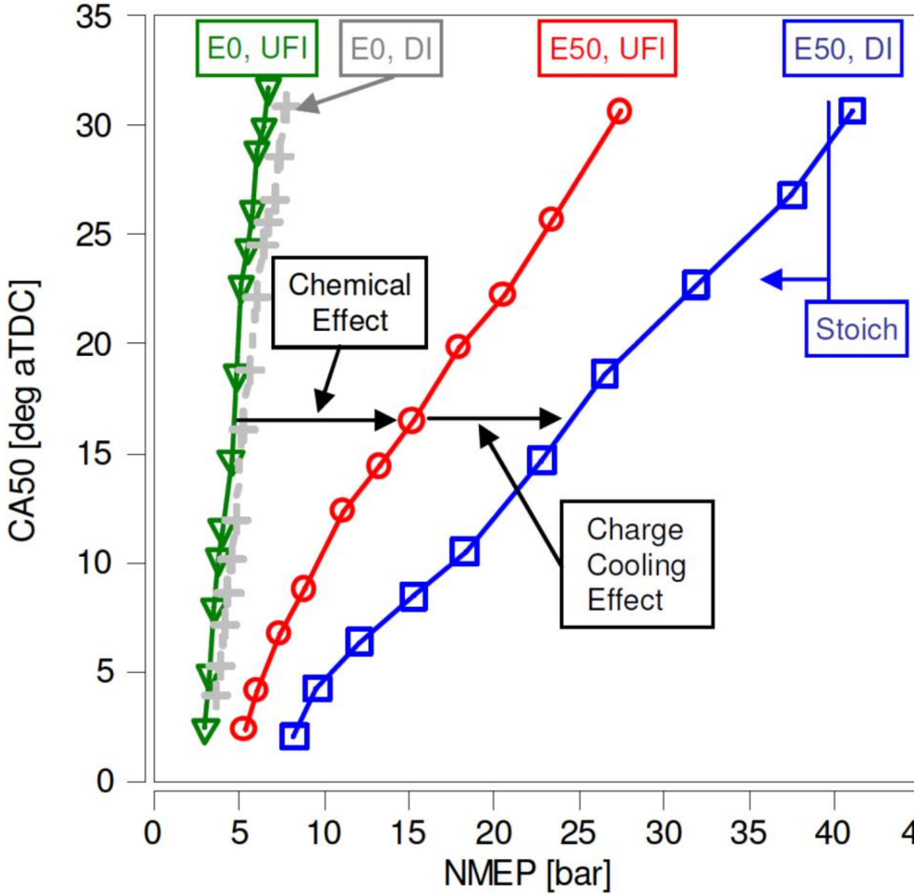
# Charge Cooling is Critical Additional Factor for Improving Anti-Knock Properties

- **HoV affects in-use anti-knock**

Knock → $T_2$ ; HoV → $T_1$

$$\frac{T_2}{T_1} = r_c^{(\gamma-1)}$$



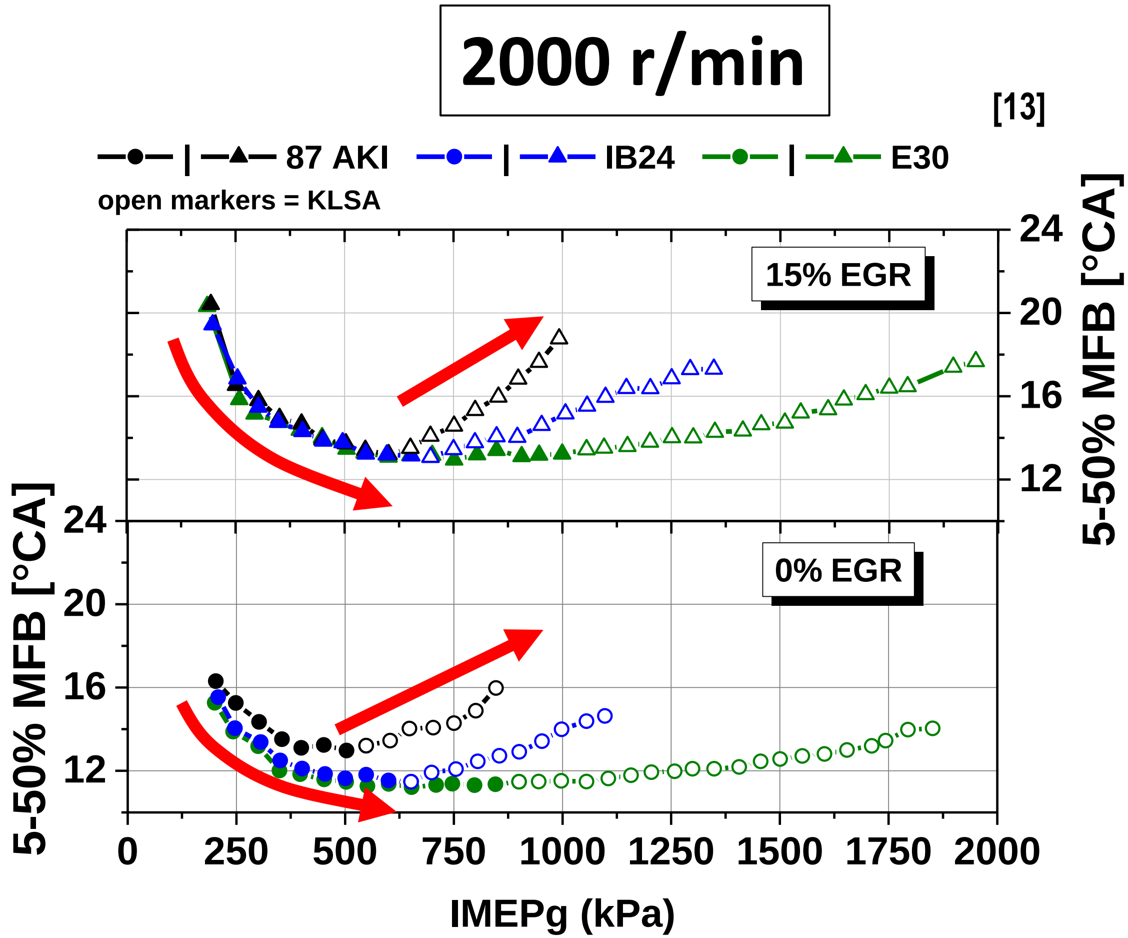




[10]

# E30 Combustion Rate Faster Than Other Fuels

- **Faster combustion reduces knock**
- **IB24 and E30 have fester combustion**
- **<u>Why?</u>**
- **Burning velocities of ethanol and i-butanol faster than gasoline***

**Is faster duration fuel, phasing, or load dominated?**

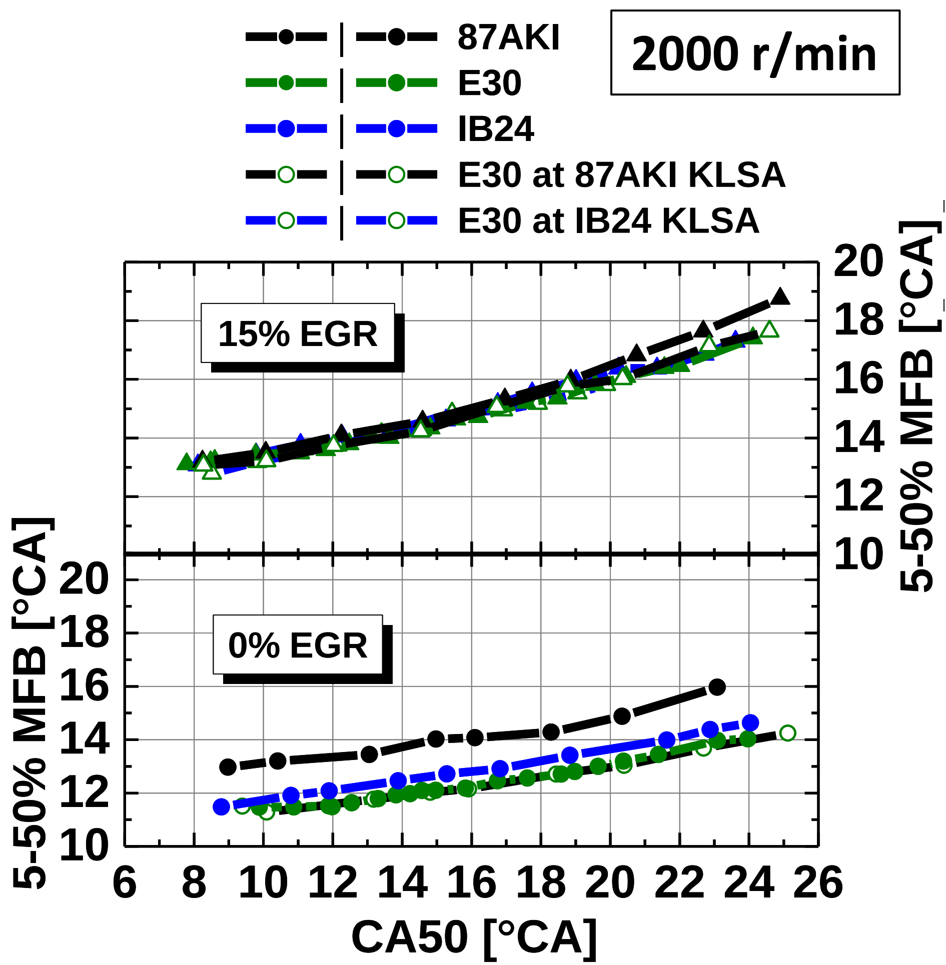



*Broustail, Guillaume, et al. "Experimental determination of laminar burning velocity for butanol and ethanol iso-octane blends." Fuel 90.1 (2011): 1-6

# Dilution is Most Dominant on 5-50 MFB Time

- **Prematurely retard E30**
- **E30 and IB24 offer chemical benefits to reducing end gas knock**

[13]



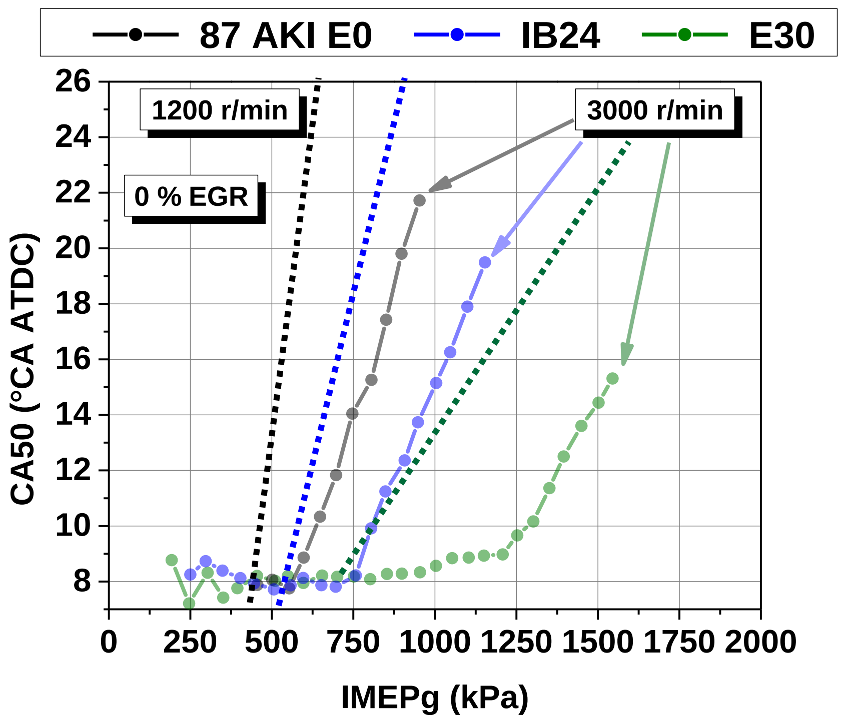

- 5-50 Rate Load Independent
- 0% EGR
  - Fuel dominates 5-50 time
- 15% EGR
  - Fuel & load independent, phasing dominates
- Kinetic & Dilution Tradeoff

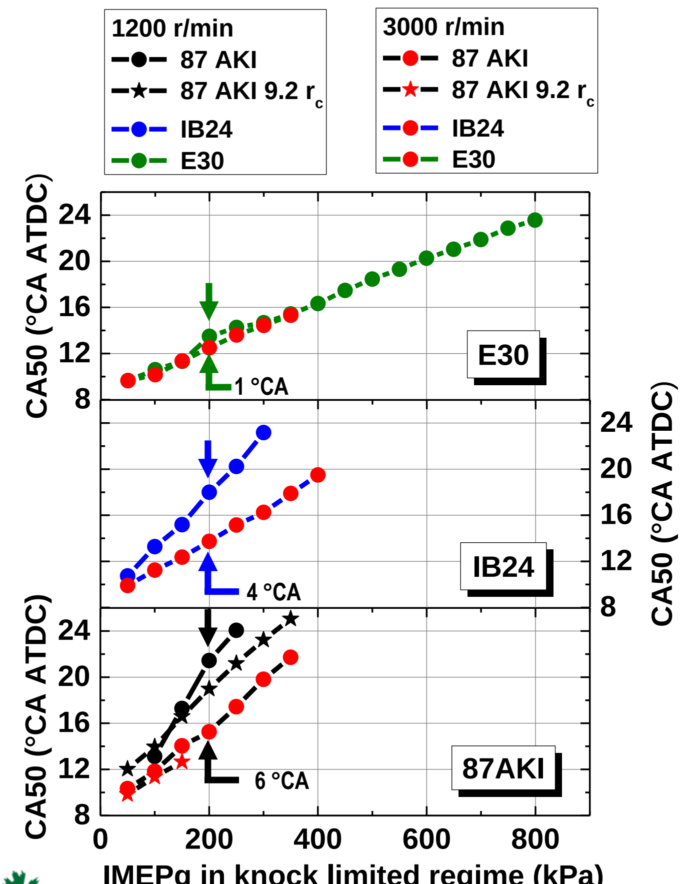
# Reduced Speed Sensitivity of E30 Improves Low-End Torque

- **E30 low-speed load much higher**
- **Onset of Knock speed dependent**
- **E30 knock trend speed independent**

| | 87 AKI | IB24 | E30 |
|---|---|---|---|
| RON (-) | 90.2 | 96.6 | 100.3 |
| MON (-) | 83.9 | 86.8 | 88.8 |
| S(-) | 6.3 | 9.8 | 11.5 |

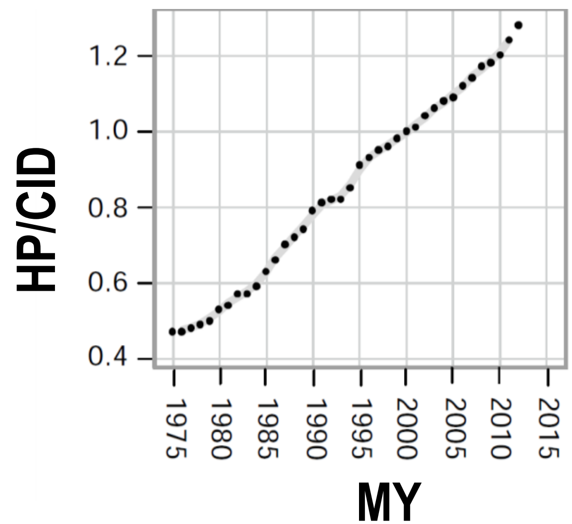
**Fuel sensitivity is important "other" factor**

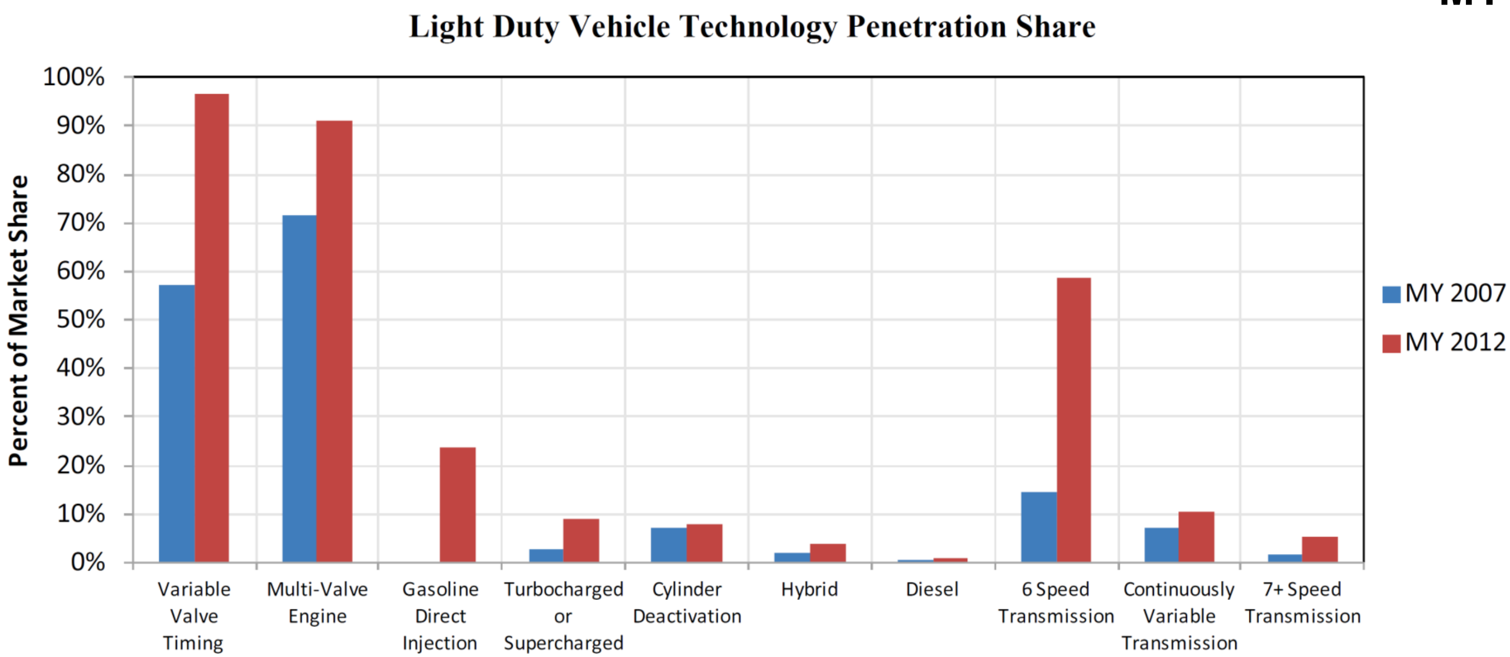


# History Has Shown That Technology Enters the LD Market

- **LD technology adoption occurring**
- **Historically has increased specific power**
  - Downsizing?

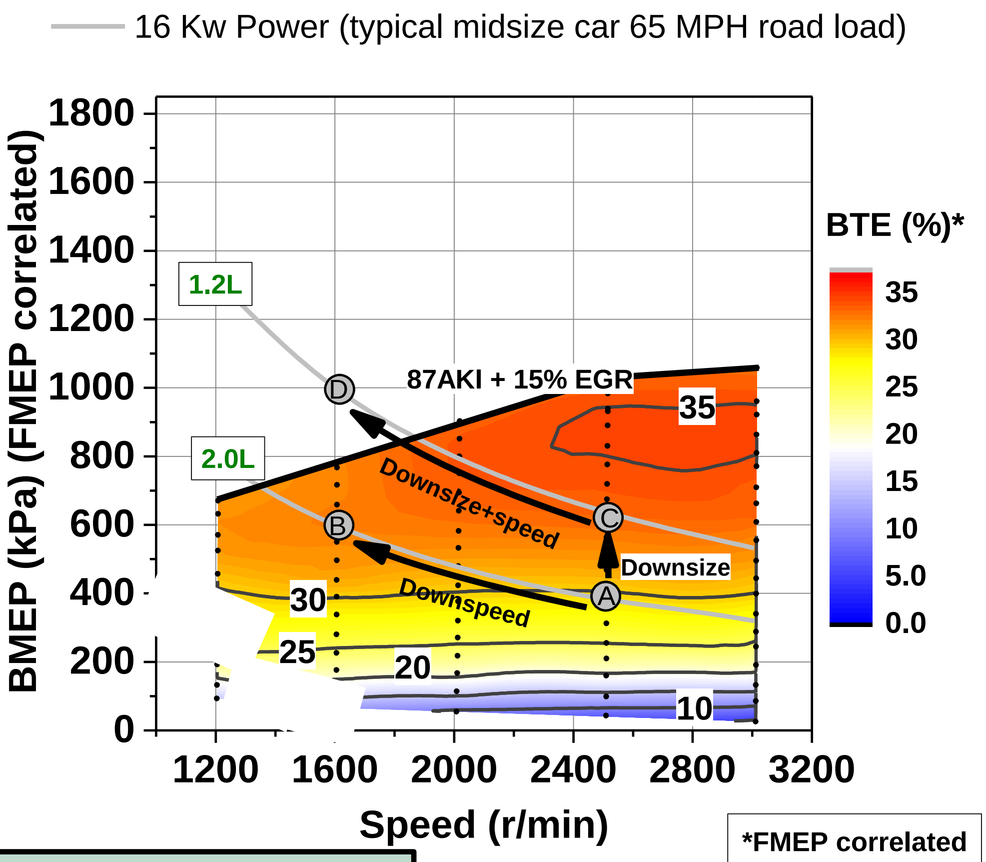



[5]

# Evolutionary Changes to Cars

- λ=1 Engine Map
- Typical midsize U.S. car
  - 65 MPH cruise = 16kW
- Lines of constant power
  - $Power = \frac{BMEP*V_d*Speed}{2*10^3}$
  - $V_d$ = 1.2 and 2L engines
    - Assume all losses same
- Assume 2.0L & transmission
- Evolutionary changes
  - B Transmission "Downspeed"
  - C Displacement "Downsize"
  - D Displacement + Transmission "Downsize+speed"




**87AKI Limits Options!**

# E30 Estimates of Economy & $CO_2$

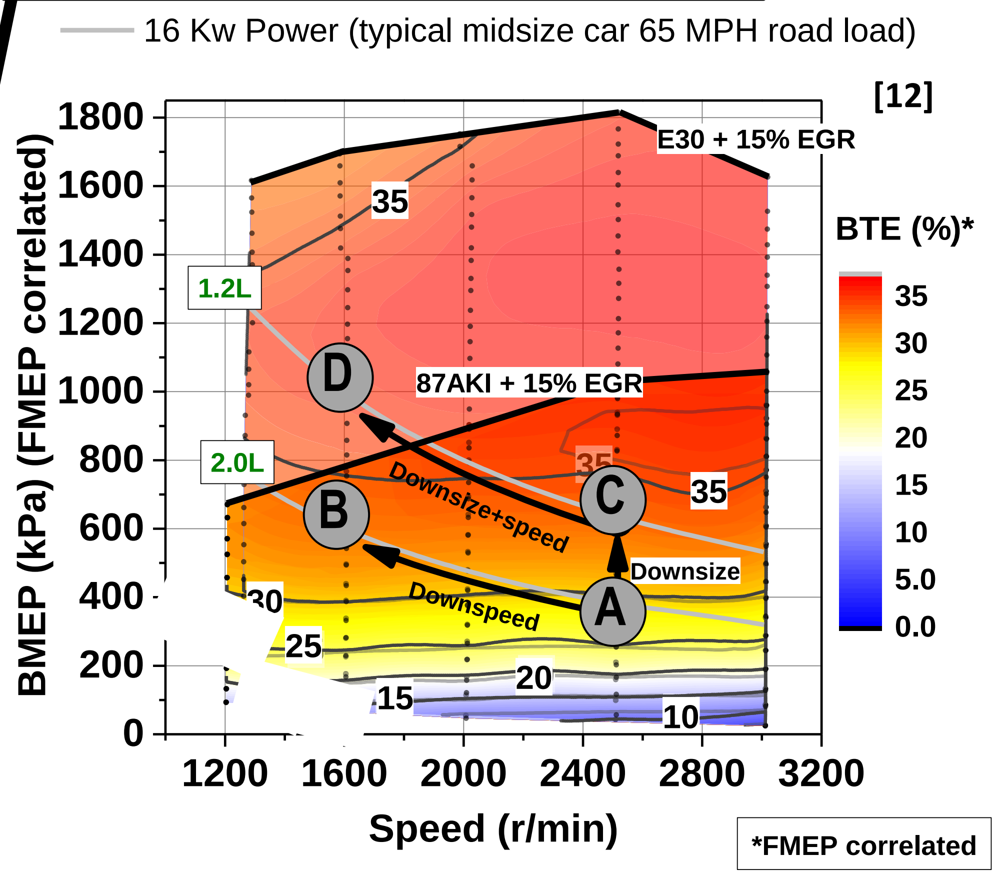
## Fuel Economy [MPG]

| | A | B | C | D |
|---|---|---|---|---|
| 87 AKI | 39.7 | 44.9 | 46.1 | NA |
| E30 | 35.7 | 40.7 | 40.9 | **43.9** |
| E30 (gas eq.) | 39.6 | 45.2 | 45.5 | 48.8 |

## Engine out [g $CO_2$/mi]

| | A | B | C | D |
|---|---|---|---|---|
| 87 AKI | **209.6** | 187.2 | 181.0 | NA |
| E30 | 210.5 | 181.8 | 177.8 | **166.0** |

- Surpasses 2020 CAFE est.
- close to 2025
- Vehicle same as 2012




**At Steady 65 Mph Cruise Up to:**
**~13.8% increase in MPG!**
**~23.5% reduction in CO2!**

# Summary

- Engines couple chemistry and mechanics
- Fuel Octane offers established technological pathway for higher η engines
- Renewable feedstocks for high octane fuels possible
  - Optimization of fuels and engines must be congruent
- Ethanol offers unique properties "beyond octane"
- EGR anti-knock effects are somewhat fuel dependent
- E30 enabled Downsized Engine (40% smaller disp. assumed)
    - Reserve power (cruise control, terrain changes, safety maneuvers, etc…)
    - 13.8% increase in MPG & 23.5% reduction in CO2
    - NHTSA 2020 MPG (Hwy) predicted, no changes to 2012 vehicle

# References


[1] http://cta.ornl.gov/data/chapter1.shtml
[2] http://www.sulphuric-acid.com/techmanual/Storage/tankcar.htm
[3] http://www.melbournemodelraceway.com.au/bachmannoo.html
[4] Environmental Protection Agency, " Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends:1975 Through 2012", available at, http://www.epa.gov/fueleconomy/fetrends/1975-2012/420r13001.pdf, accessed May 2, 2013.
[5] National Highway Traffic Safety Administration and Environmental Protection Agency, "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule" available at http://www.nhtsa.gov/fuel-economy, accessed May 2, 2013
[6] Caton, J., "A Review of Investigations Using the Second Law of Thermodynamics to Study Internal-Combustion Engines," SAE Technical Paper 2000-01-1081, 2000, doi:10.4271/2000-01-1081.
[7] Foster D.E., "Low Temperature Combustion- A Thermodynamic Pathway to High Efficiency Engines", National Petroleum Council Fuels Study, prepared March 2012, http://www.npc.org/FTF_Topic_papers/6-Low_Temperature_Combustion.pdf.
[8] Grandin, Börje, et al. "The effect of knock on the heat transfer in an SI engine: Thermal boundary layer investigation using CARS temperature measurements and heat flux measurements." *SAE transactions* 109.3 (2000): 2003-2016.
[9] Leppard, William R. *The chemical origin of fuel octane sensitivity*. No. CONF-9010205--. Warrendale, PA (USA); Society of Automotive Engineers, 1990.
[10]Stein et al. SAE Int. J. Fuels Lubr./Volume 5, Issue 2 (May 2012), SAE 2012-01-1277
[11] http://www.dailytech.com/With+the+Addition+of+Cooled+EGR+Ford+Has+a+Gas+Engine+to+Rival+Diesels/article18126.htm
[12] Splitter, Derek Allan, and James P. Szybist. "An Experimental Investigation of Spark-Ignited Combustion with High-Octane Bio-Fuels and EGR, Part 1 of 2 Engine Load Range and Downsize Downspeed Opportunity." *Energy & Fuels* (2013).
[13] Splitter, Derek Allan, and James P. Szybist. "An Experimental Investigation of Spark-Ignited Combustion with High-Octane Bio-Fuels and EGR, Part 2 of 2 Fuel and EGR Effects on Knock Limited Load and Speed." *Energy & Fuels* (2013).
[14] Lavoie, George A., Elliott Ortiz-Soto, Aristotelis Babajimopoulos, Jason B. Martz, and Dennis N. Assanis. "Thermodynamic sweet spot for high-efficiency, dilute, boosted gasoline engines." International Journal of Engine Research 14, no. 3 (2013): 260-278.
[15] http://www.me.berkeley.edu/gri_mech/version30/figs30/f1.gif
[16] Wagner, R. M., James A. Drallmeier, and C. Stuart Daw. "Characterization of lean combustion instability in premixed charge spark ignition engines." *International Journal of Engine Research* 1, no. 4 (2000): 301-320.
[17] Caton J.A, "On the destruction of availability (exergy) due to combustion processes -with specific application to internal-combustion engines", Energy, Volume 25, Issue 11, November 2000, Pages 1097-1117, 2000.
[18]Kokjohn, S. L., R. M. Hanson, D. A. Splitter, and R. D. Reitz. "Fuel reactivity controlled compression ignition (RCCI): a pathway to controlled high-efficiency clean combustion." *International Journal of Engine Research* 12, no. 3 (2011): 209-226.
[19]Splitter, D., Hanson, R., Kokjohn, S., and Reitz, R., "Reactivity Controlled Compression Ignition (RCCI) Heavy-Duty Engine Operation at Mid-and High-Loads with Conventional and Alternative Fuels," SAE Technical Paper 2011-01-0363, 2011, doi:10.4271/2011-01-0363.
[20] Splitter, D., Wissink, M., DelVescovo, D., and Reitz, R., "RCCI Engine Operation Towards 60% Thermal Efficiency," SAE Technical Paper 2013-01-0279, 2013, doi:10.4271/2013-01-0279.
[21] Sandia CRF website May2011

# Questions?

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