High Octane Ethanol Blends for Improved Vehicle Efficiency

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Fueling American Growth
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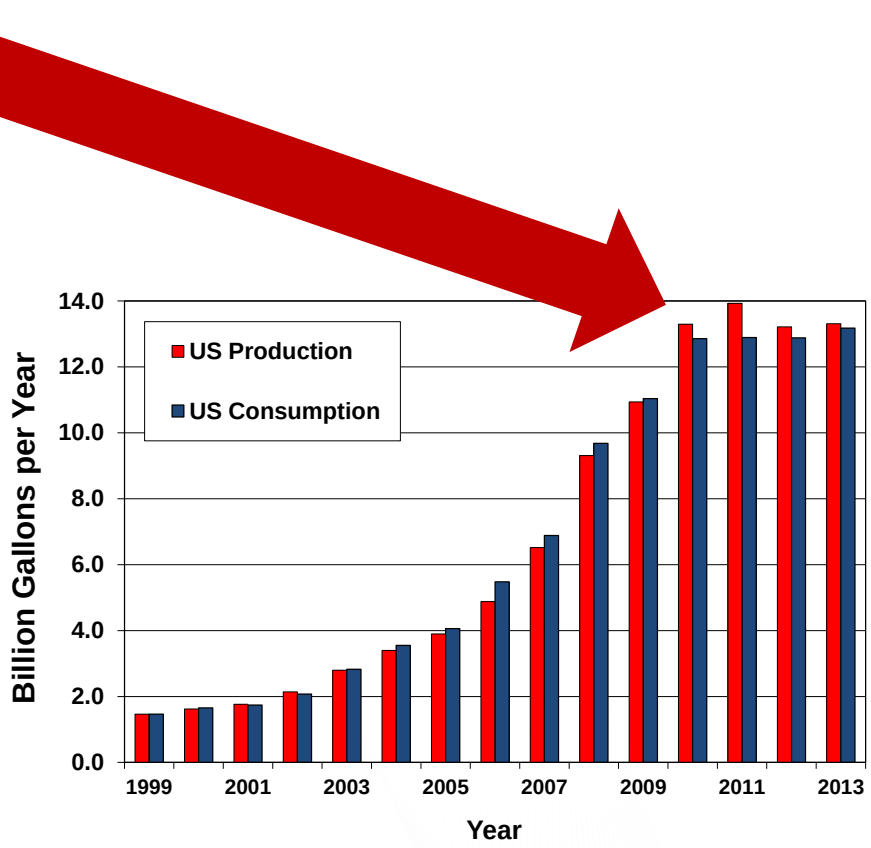
Work Supported by U.S. Department of Energy

Ethanol is currently our largest volume biofuel

- But, we are at the "Blend Wall"
- Over 99% of domestic ethanol is used in E10
- Where can we go from here?
  - E15
    - *Legal* in 2001 and newer vehicles
    - Several manufacturers permit E15 in their new vehicles
  - FFV fuel underutilized
  - What about a new *high-octane* mid-level blend?



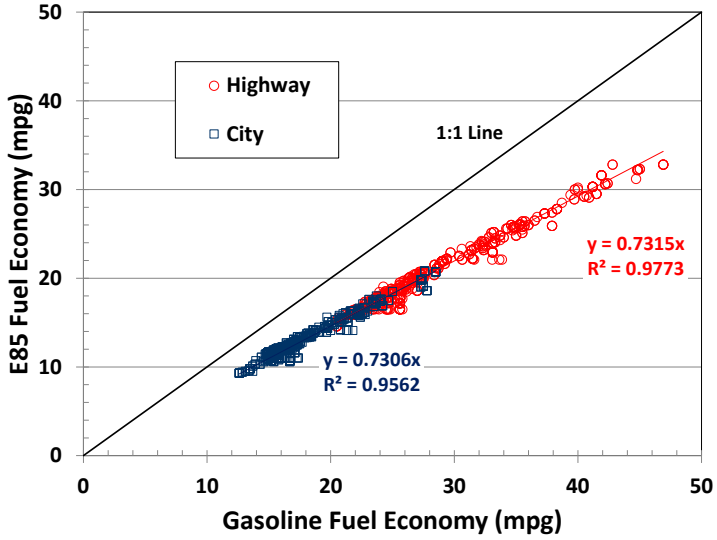
U.S. Ethanol production.
Data from Energy Information Agency
http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf

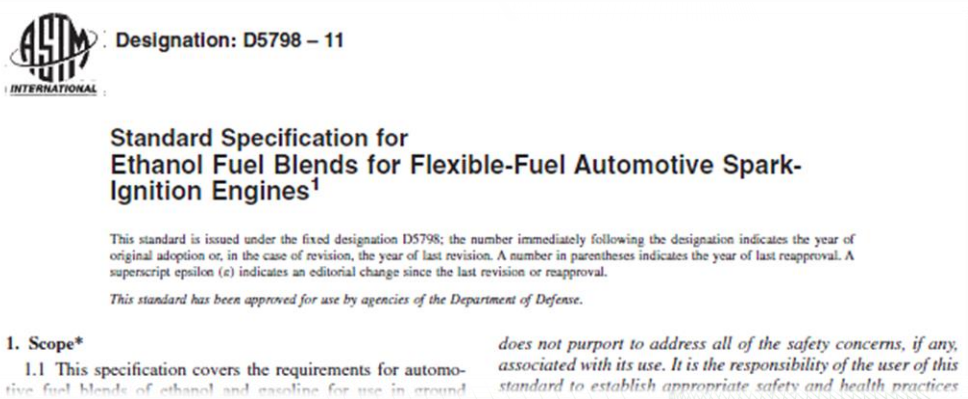
Flex Fuel Vehicles (FFVs) Can Use Any Blend of Ethanol.

Consumers Continue to Shy Away from "E85"

- **Gasoline stations average over 2000 gal/station/day**
- **E85 dispensers average <250 gal/dispenser/day**
  - >17M FFVs on road – **annually consume ~13 gal E85 per vehicle**
- **Lower Energy Density and often higher $/BTU** (compared to gasoline or E10)
  - Shortened range
  - Higher cost per mile
- **How much ethanol is in my "E85?"**
  - ASTM spec for "Fuel for FFVs" allows 51% to 83% ethanol
    - Specification addresses quality and volatility of blends
    - Potential for significant variability in vehicle fuel economy
    - Contributes to consumer confusion

Consumer acceptance is key to success of any new fuel





Designation: D5798 – 11

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

This standard is issued under the fixed designation D5798; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope*

1.1 This specification covers the requirements for automo-

does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices

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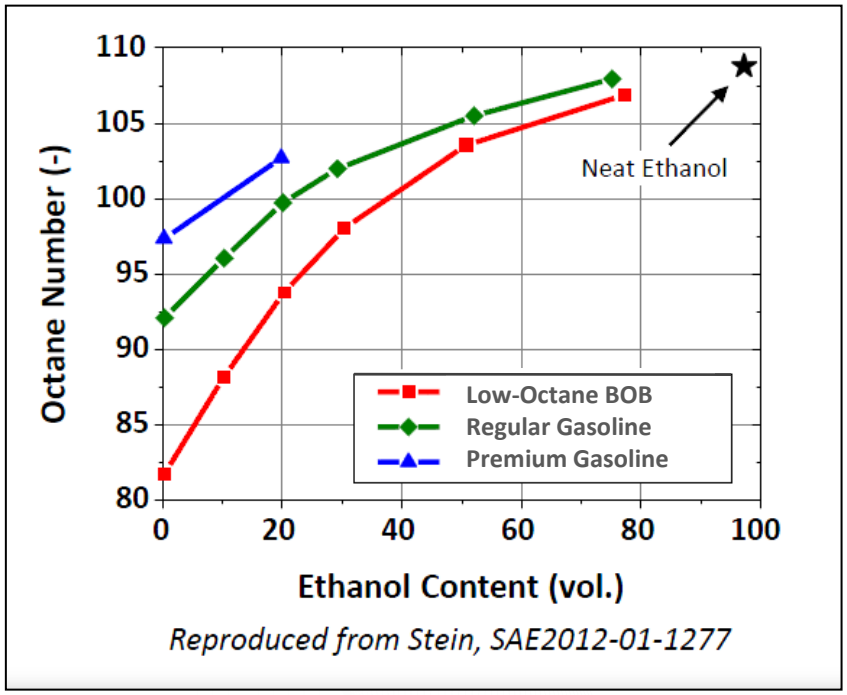
Ethanol is a very effective octane booster

- ~2/3rd of octane benefit from first 1/3rd of ethanol volume percent
- EPA opened the door for a high octane ~E30 fuel in Tier 3 rule
  - "…we allow vehicle manufacturers to request approval for … fuel such as a high-octane 30 percent ethanol … blend (E30) for vehicles … optimized for such fuel"
- Road fuel infrastructure for a mid-level ethanol blend is not trivial (but significantly less complex than many other alternatives)
  - Over 3000 E85 dispensers in service, over 17M FFVs on the road that could use an E25-E40 fuel *today*
  - Thousands of dispensers replaced annually. ***Invest in upgraded dispensers now***



Reproduced from Stein, SAE2012-01-1277

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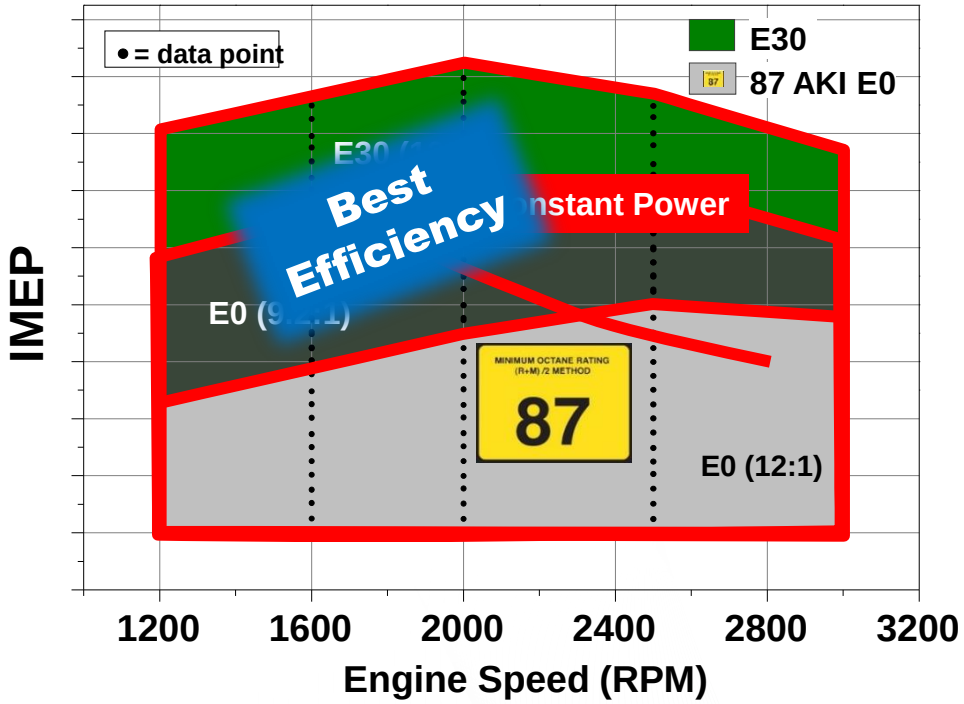
Recent Experiments Highlight Efficiency Benefits of High Octane Fuel for SI engines

- **Engines can make more torque and power with higher octane fuel**
- **Ethanol is very effective at boosting octane number**
- **Increased torque enables downspeeding and downsizing for improved fuel economy**
  - For future vehicles, engine and system efficiency can balance lower energy density of ethanol blends



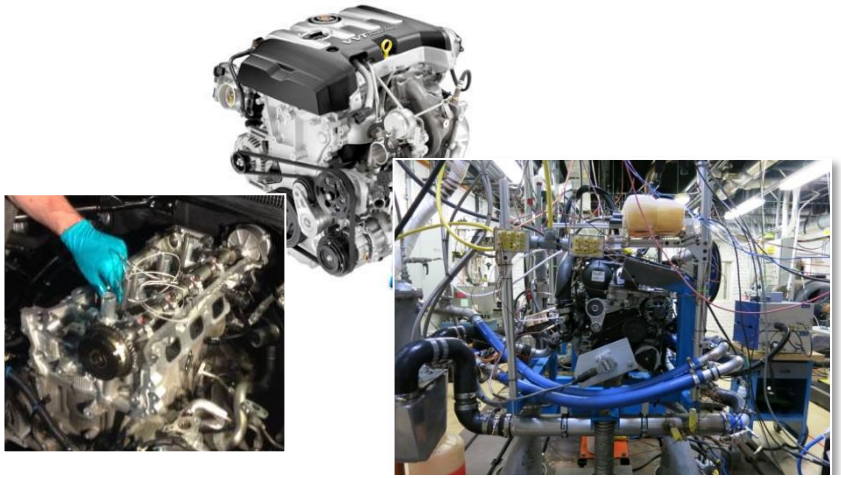
In a high compression research engine, high-octane E30 enables doubling of available torque compared to 87 AKI E0 fuel

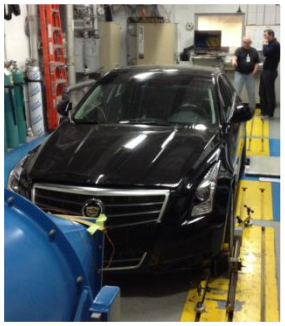
- Splitter and Szybist, ORNL

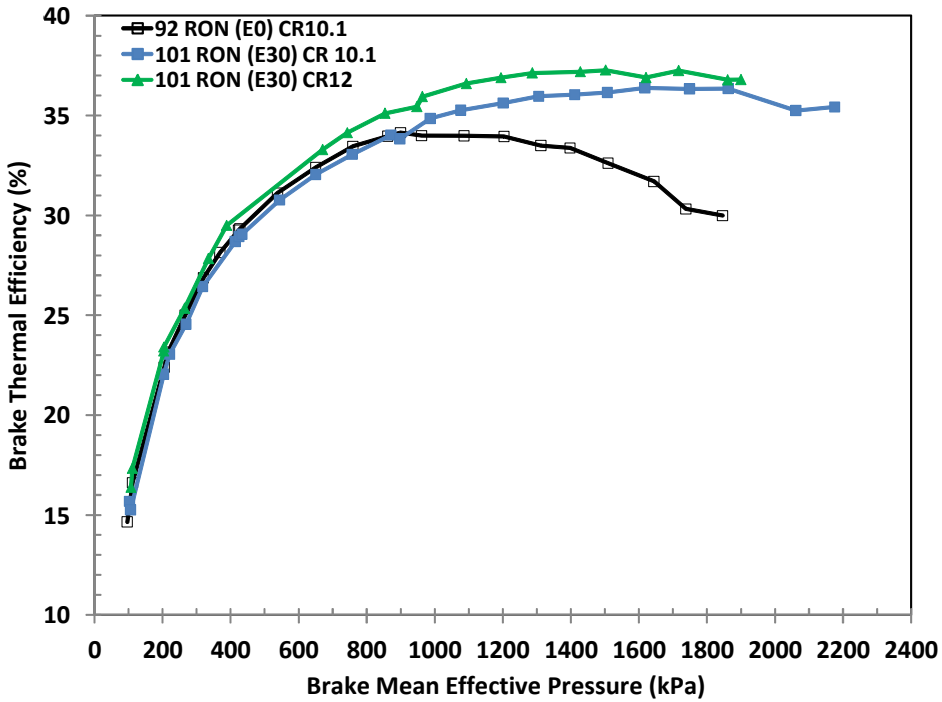
A New High Octane Fuel Could Make Better Use of Ethanol's Properties, Moving The Nation Toward Multiple Goals

- **Engine efficiency can improve with increasing ethanol and octane**
- **Data suggest that E25-E40 blend in future vehicles can return equivalent "tank mileage" as E10 in conventional vehicles**
  - Energy density penalty is *linear* with increasing ethanol concentration,
  - Power and efficiency gains are *non-linear*
  - **Volumetric Fuel Economy Parity means *every gallon of ethanol* displaces *a gallon of gasoline***
    - CAFE (fuel economy) benefit to OEM is significant
    - GHG Benefit is significant
  - Can help nation achieve RFS compliance
  - **Legal to use in >17M legacy FFVs**

Industry and DOE Investing In Programs to Quantify Efficiency and GHG Benefits of High Octane Fuels







DOE Work supported by

- **Vehicle Technologies Office**
- **BioEnergy Technologies Office**
- **Studies quantifying**
  - Efficiency and performance improvements in engines/vehicles with high octane fuels, various sources of octane, different engine architectures
  - GHG benefits
  - Market analysis,
  - Infrastructure compatibility

Industry Cost-Share, Funds-in, and Tech Support

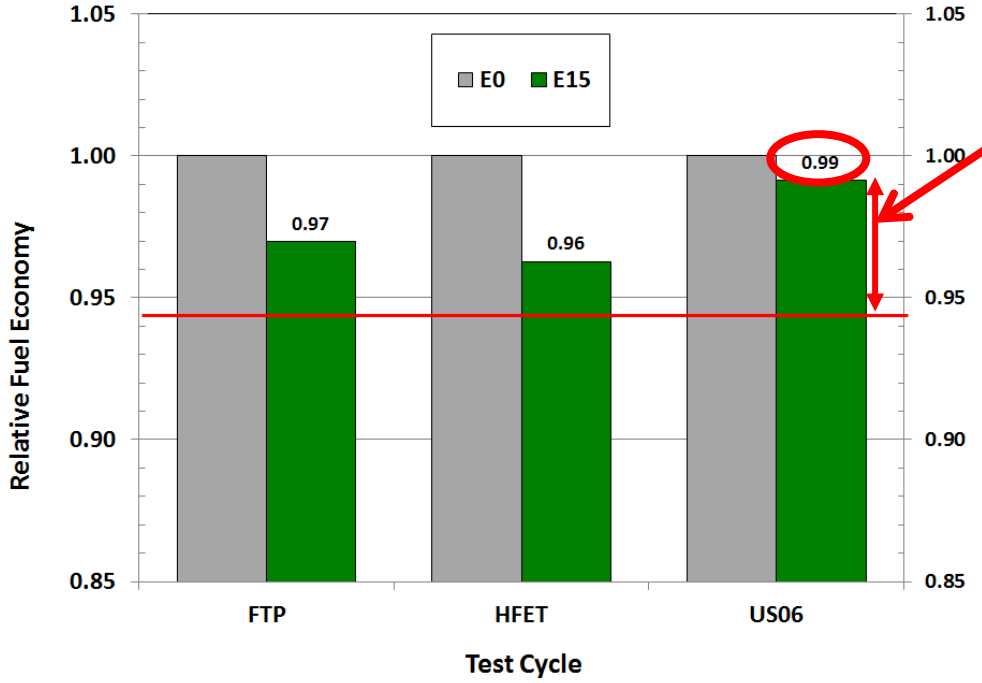
- **Ford**
- **General Motors**
- **Coordinating Research Council**

←Thermal Efficiency of Ford EcoBoost

(data from Sluder, ORNL)

Benefits of Engine Downsizing with High Octane E-Blend Demonstrated on Late-Model Turbo GDI Vehicle

- **E15-Compatible Ford EcoBoost Fiesta**
  - 1.0 liter, 3-cylinder turbo GDI engine
- **Owner's Manual:** "Regular unleaded gasoline…is recommended….premium fuel will provide improved performance and is recommended for severe duty usage…"
- **Experiment:**
  - Blend regular 87 AKI E0 with 15% Ethanol
    - Boosts octane, lowers energy content
  - Test on FTP, HFET, and US06 (high-load cycle)
  - *No Changes* to engine, vehicle, calibration or shift schedule
  - Results within 1% of Volumetric Fuel Economy Parity with E15 on US06



4.6% Efficiency Improvement

Fuel:	E0	E15
RON	90.7	97.8
AKI	87.7	92.6
Btu/gal	113,100	106,700
Relative Btu/gal	1.00	.943

Addition of 15% ethanol boosts octane, improves engine performance & efficiency.

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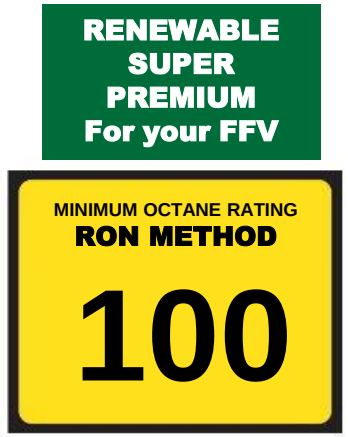
Vehicle Study to Determine Potential Performance Improvement of Legacy FFVs with RSP

Work supported by DOE BioEnergy Technologies Office

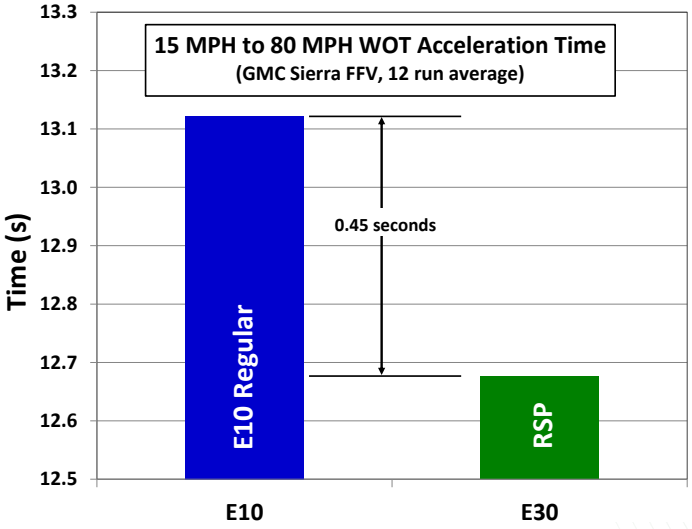
- **Motivation: Measureable performance improvement in legacy FFVs could enable early adoption of "Renewable Super Premium for Your FFV"**
- **Acquired 4 "ethanol tolerant" FFVs**
  - GMC Sierra
  - Chevrolet Impala
  - Ford F150
  - Dodge Caravan
- **Prep and Baseline "wide open throttle" WOT test with Regular E10**
- **Prep and WOT test with ~100 RON E30**
- **Report available:**
  - 3 of 4 FFVs show acceleration improvement with E30
    - ORNL's Sierra results with E30 similar to Car and Driver test with E85 ➔

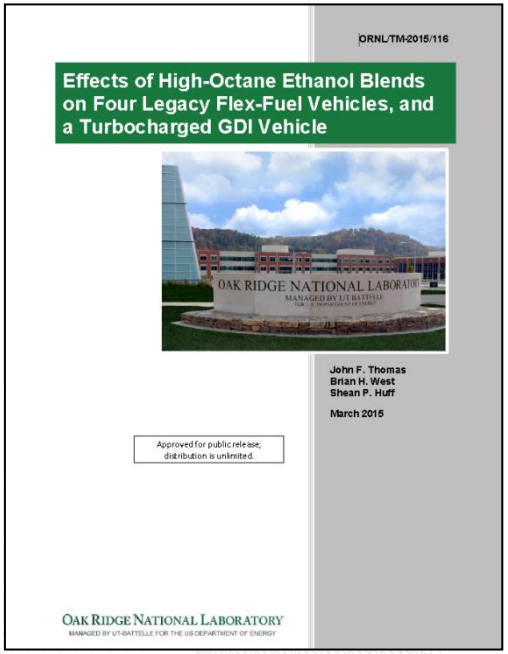
If *half* FFVs on road today filled up with RSP *half* the time, consume *half-billion* gallons more ethanol!



Car and Driver FFV test shows 0.4 second faster 0-60 mph time with E85

www.caranddriver.com/reviews/2014-chevrolet-silverado-v-6-instrumented-test-review





http://info.ornl.gov/sites/publications/Files/Pub54888.pdf

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Regulations Have Required Some Changes; Many in Coordination with Emissions and Fuel Economy Laws. Some examples:

- 1974 Unleaded Gasoline
- 1979 E10 Ethanol Subsim Waiver
- 1981 Tier 0
- 1986 "R factor" Fuel Economy Calculation
- 1989 Phase 1 Gasoline Summer RVP Limits
- 1991 Phase 2 Gasoline Summer RVP Limits (including 1-psi E10 waiver)
- 1992 Winter Oxyfuels Program (39 cities)
- 1993 Highway diesel fuel sulfur control (500 ppm)
- 1994 Tier 1
- 1995 Phase 1 RFG and Anti-dumping
- 1996 Prohibition on lead
- 1999 NLEV
- 2000 Phase 2 RFG
- 2002 Mobil Source Air Toxics (MSAT1)
- 2004 Tier 2 Gasoline Sulfur Control (30 ppm avg, 80 cap)
- 2006 Renewable Fuels Standard
- 2006 Removal of RFG Oxy Mandate
- 2006 Ultra Low Sulfur Highway Diesel Fuel (15 ppm)
- 2006 Boutique Fuels List
- 2007 Renewable Fuel Standard (RFS)
- 2010 Ultra Low Sulfur Nonroad Diesel Fuel (15 ppm)
- 2010 Renewable Fuel Standard 2 (RFS2)
- 2010 E15 Waiver
- 2011 MSAT2 – Gasoline Benzene
- 2017 Tier 3, Gasoline sulfur <10 ppm, 30 mg/mi NMOG+NOx, E10 cert fuel

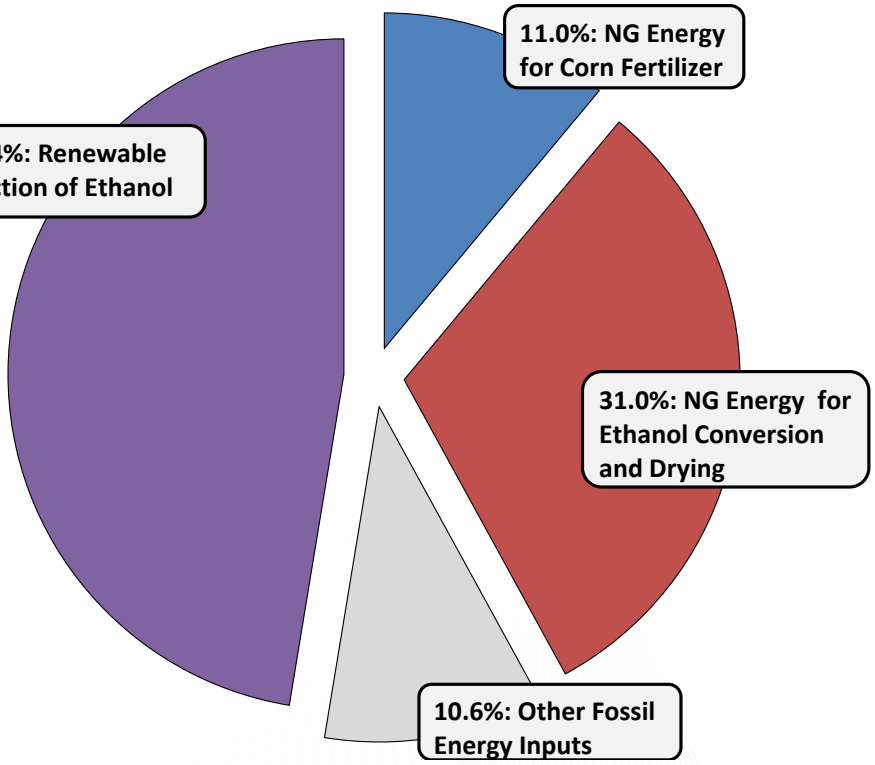
Regulating Octane in the US would not be a new precedent

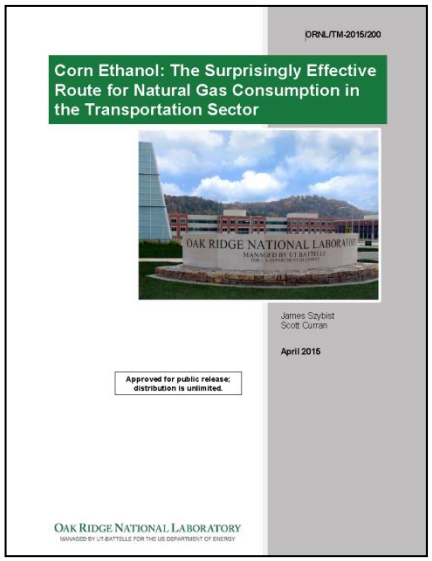
Regular fuel in Europe is 95 RON (similar to Premium in US)

Energy Security Bonus:

Corn Ethanol Is An Effective Means Of Putting Domestic Natural Gas Into The Transportation System

- **Ethanol is 47% renewable**
- **42% of energy in ethanol *from natural gas***
- **13.3 billion gallons ethanol in 2013**
  - 8.4B GGE (gallons gasoline equivalent)
  - 3.5B GGE of natural gas
  - ***Equivalent to 6.8M light-duty CNG vehicles!***
  - (~150,000 CNG vehicles in U.S., 15M worldwide)




ORNL/TM-2015/200

Corn Ethanol: The Surprisingly Effective Route for Natural Gas Consumption in the Transportation Sector

OAK RIDGE NATIONAL LABORATORY

James Szybist
Scott Curran

April 2015

Approved for public release; distribution is unlimited.

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References
Szybist and Curran, ORNL/TM-2015/200
http://info.ornl.gov/sites/publications/Files/Pub55581.pdf

http://www.afdc.energy.gov/vehicles/natural_gas.html

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The Road to Higher Octane Blends

(One Person's *Opinion* on Some Potential Routes)

- Maintain RFS, let RINs work
- Maintain OEM incentive to build FFVs
- Continue to build out Flex-Fuel and/or E25 Infrastructure
- Offer High-Octane E25 as "Renewable Super Premium for your FFV"
  - Conduct a Market Study!
  - Price RSP below regular, or at least between 87 octane regular and "normal premium"
    - Oil will not be $50/bbl forever!
- Avoid blending E15 with even lower octane blendstocks
  - E15 in a "good" blendstock can make midgrade or premium
- Remember that domestic corn ethanol is a GHG win, even when gallon of ethanol displaces 2/3rd of gallon of gasoline
  - Cellulosic is even better
  - Both are better still when a gallon of ethanol displaces a *full gallon* of gasoline!
  - Don't overlook other potential fuels (e.g., butanol)
- **Long range:** Focus on fuel *performance*; New fuel spec for "RSP" should relate to engine anti-knock performance, not necessarily Exx.
  - Performance specification can likely be met with array of components (ethanol, butanol, bio-derived HCs, refinery streams)

Acknowledgements

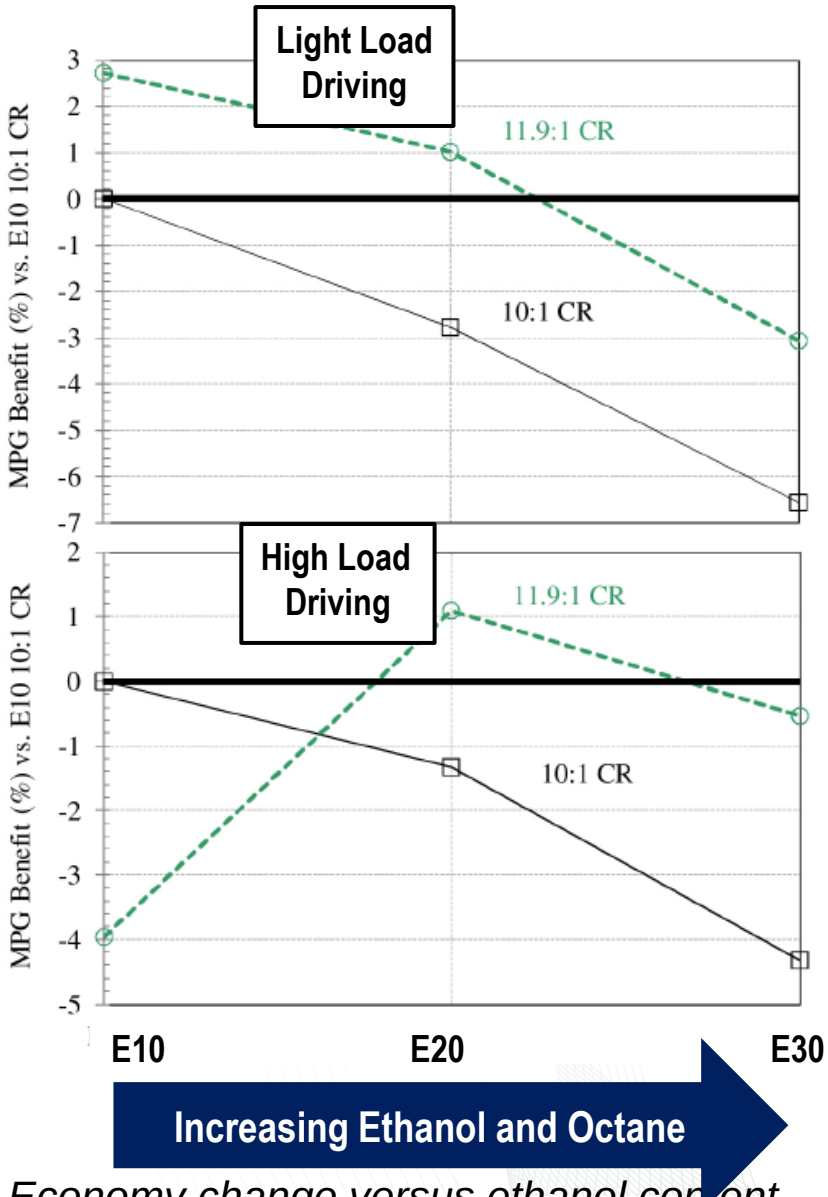
- Alicia Lindauer at DOE BioEnergy Technologies Office
- Kevin Stork at DOE Vehicle Technologies Office
- ORNL, NREL, and ANL colleagues
- Ford, GM, and CRC

Backup Slides

Recent Ford Data Shows Improved Fuel Economy with High Octane Ethanol Blends

- **Ford developed engine maps with three ethanol blends at 2 compression ratios**
- **Modeled vehicle fuel consumption**
  - Changed shift schedule for modest down-speeding
- **At light load (highway test)**
  - Higher compression boosts fuel economy with all fuels
  - Fuel economy tracks ethanol content
- **At higher loads (US06 aggressive test)**
  - Higher compression boosts fuel economy with higher octane blends

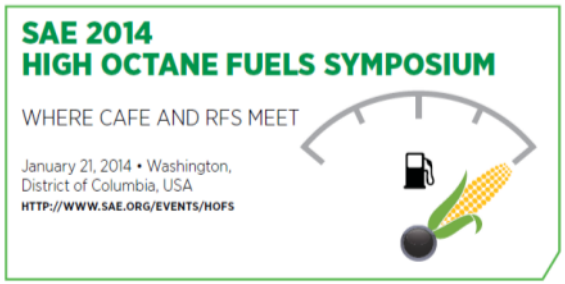
- **Ethanol can do so much more than bring sub-octane gasoline (BOB) up to 87 AKI and displace 2/3^{rds} of a gallon of gasoline**



Fuel Economy change versus ethanol content (from Jung, et al, SAE 2013-01-1321)

ORNL Organized SAE High Octane Fuels Symposiums (January 2013 and 2014)

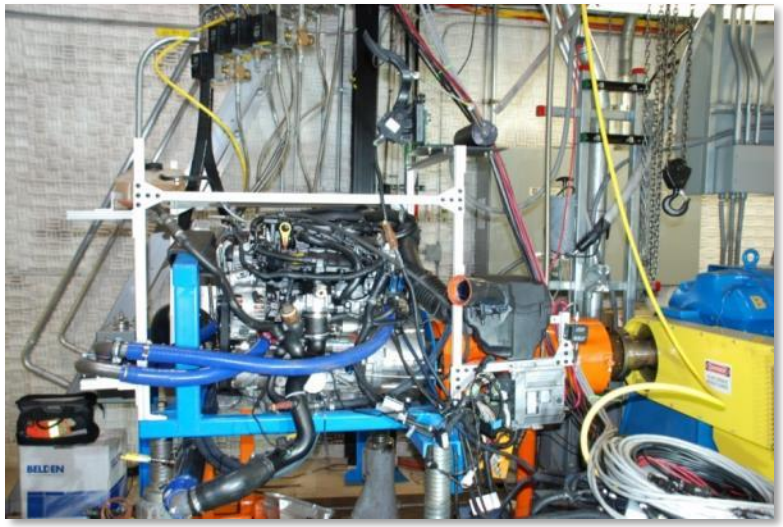
- **Symposiums brought together stakeholders and technical experts**
  - Speakers from regulatory agencies, OEMs, energy companies, convenience stores, academia, infrastructure

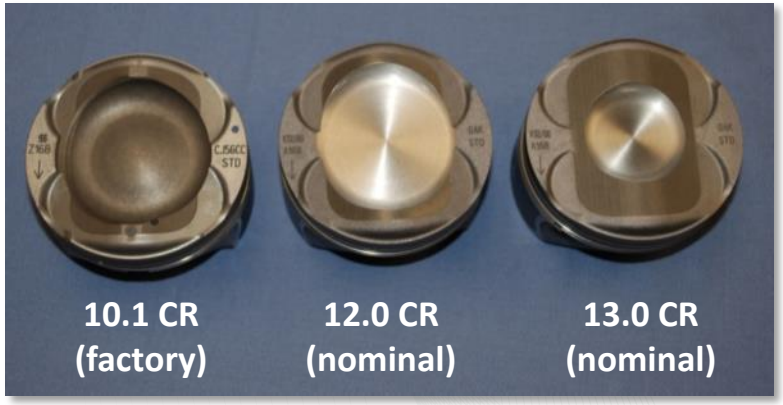


- **Synergies exist between RFS and CAFE through ethanol**
  - Well-established efficiency benefit to high ethanol fuel blends (ORNL and others) due to high chemical octane number and high latent heat of vaporization
  - Anti-knock properties of ethanol allow high compression ratio and aggressive downsizing
  - Efficiency advantage can overcome energy density penalty at approx E20-E40 in optimized engine/vehicle
- **Switching to a new fuel on a national scale is significant undertaking**
  - EPA regulatory authority not straight-forward: reliant on GHG emissions, numerous hurdles
  - OEMs conflicted: concerns over mis-fueling, fuel availability, and fuel pricing
  - Oil industry opposed to new fuel: lifecycle GHG emissions unclear, RFS should be revised or repealed because of lack of cellulosic ethanol, premium grade gasoline already available
- **Regulatory and infrastructure challenges are nontrivial**

Two Projects Using Ford 1.6 Liter EcoBoost To Explore High Octane Fuels and Engine Compression Ratio Synergies

- **Turbo-charged, direct-injection engine**
  - Full engine control provided by Ford
  - High compression pistons have been designed and machined
  - Supporting both DOE and CRC projects
- **Fuel blends will span various octane levels with different sources of octane number**
- **Full Engine maps with emissions and efficiency to support vehicle modeling**





Primary work supported by DOE Vehicle Technologies Office, engine and technical support from Ford

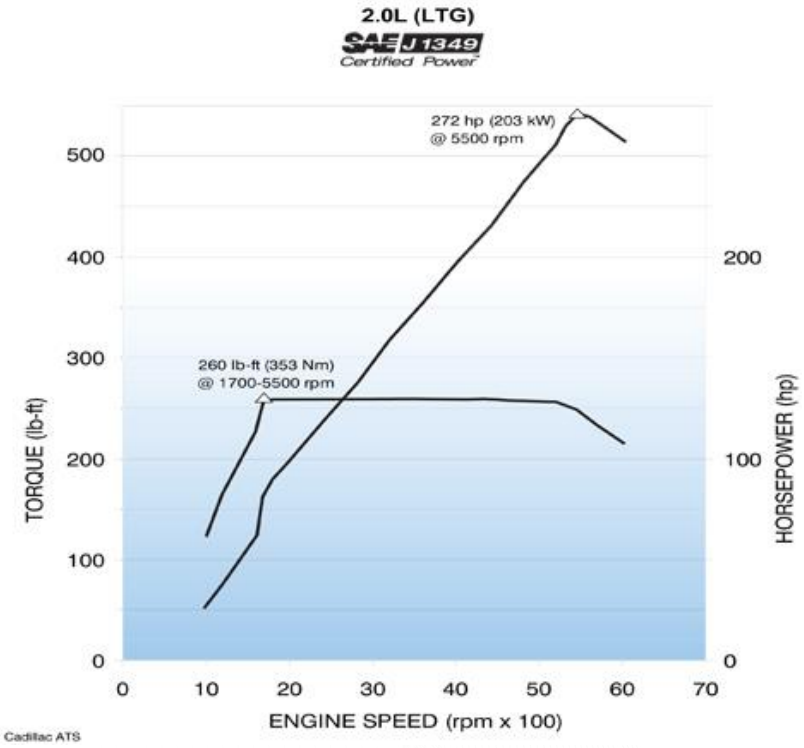
CRC funds-in effort also underway (AVFL-20)*

*http://www.crcao.com/about/Annual%20Report/2013%20Annual%20Report/2014%20Annual%20Report/AR2014Final.pdf

DOE Funding Opportunity (Competitive), FOA991 Recently Awarded

Gasoline Engine and Fuels Offering Reduced fuel Consumption and Emissions

- **GM 2.0 LTG Engine**
- **Cost share with CRC**
- **Technical support from GM**
- **Target 25% reduction in petroleum consumption**



Work supported by DOE Vehicle Technologies Office, engine and technical support from GM/CRC

CRC project AVFL-26*

New LTG engine is excellent candidate for downspeeding/downsizing enabled with high-octane fuels

**http://www.crcao.com/about/Annual%20Report/2013%20Annual%20Report/2014%20Annual%20Report/AR2014Final.pdf*

Multi-Lab Team (NREL/ANL/ORNL) Conducting "Renewable Super Premium" (RSP) Study

Explore Benefits/Challenges of New High-Octane Mid Level Blend

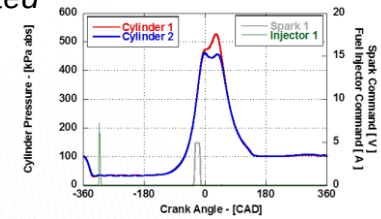
(BioEnergy Technologies Office)

- **Infrastructure compatibility (NREL & ORNL)**
- **Market analysis (NREL & ORNL)**
- **Well-to-wheels analysis (ANL Lead)**
- **Quantification of RSP knock resistance properties (NREL)**
- **Fuel economy Potential In Dedicated RSP Vehicle (ORNL)**
- **Effect of RSP on legacy FFVs (ORNL)**

High-Octane Efficiency Benefits Demonstrated at the Vehicle Level

- **GM ATS with 2.0 Turbo GDI engine**
  - Same LTG engine as DOE/CRC study
  - Manual Transmission will readily enable downspeeding
  - Currently conducting baseline tests on range of fuels with factory pistons/calibration
  - Change to high compression ratio, revise calibration
  - Fuel blends will span various octane levels with different sources of octane number
- **Demonstrate downspeeding/downsizing**
  - Vary shift schedule and/or change final drive
  - Change dyno setup to simulate larger vehicle (test weight, coefficients)

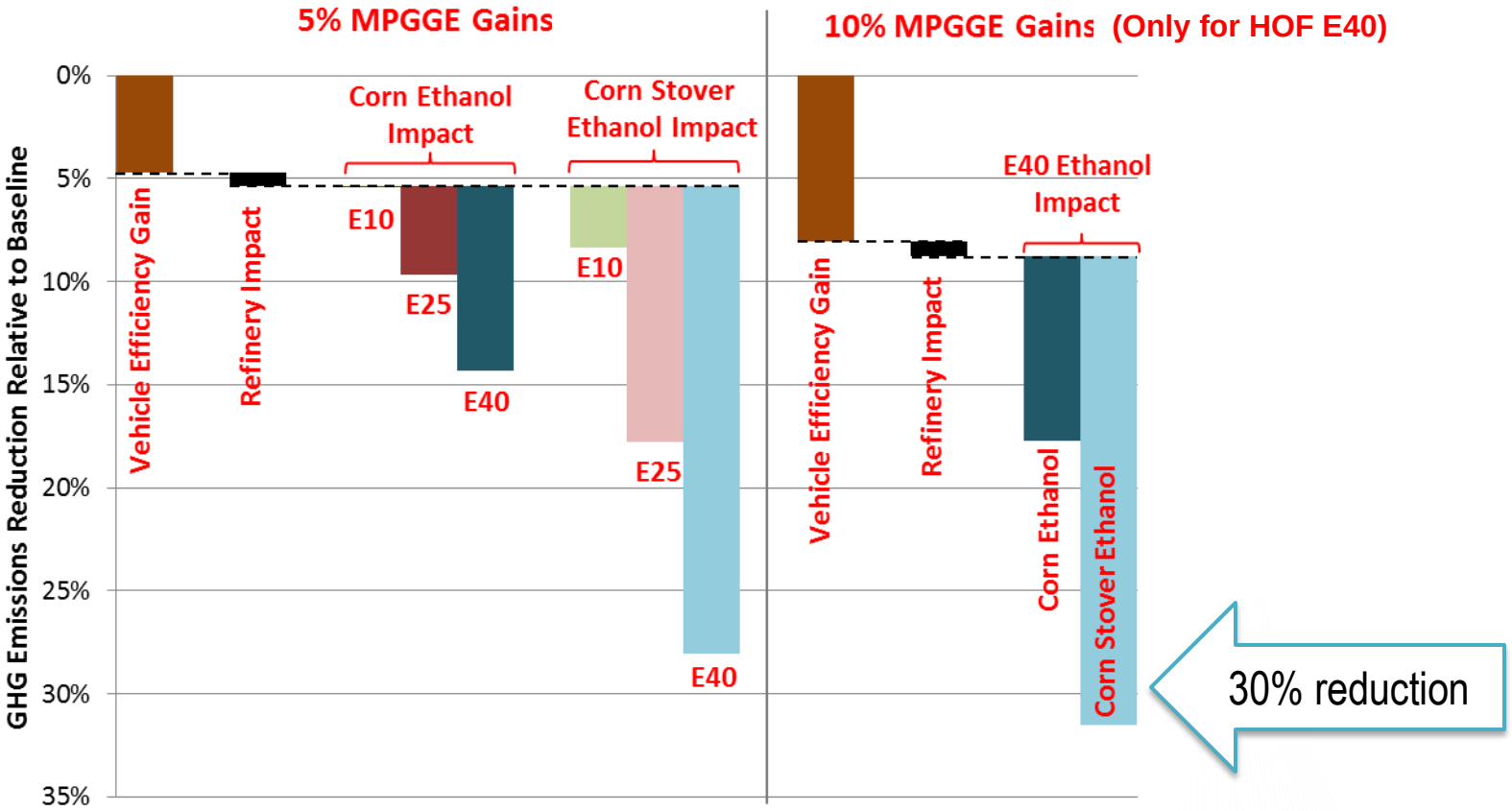
Cadillac ATS acquired. Instrumented cylinder head installed to support combustion analysis



- *GM Tech support*
  - *High compression pistons*
  - *Engine controls support (spark, boost, etc)*
  - ✓ *Ability to monitor cylinder pressure*
  - ✓ *Source for taller gears (final drive ratio)*

Work supported by DOE Bioenergy Technologies Office,
GM technical support (vehicle uses same engine as DOE FOA project [CRC AVFL-26])

High Octane Ethanol Blends Reduce Life Cycle GHG Emissions
(ANL analysis from BETO effort)



- GHG reductions due to efficiency gains: 5-9% respectively
- Minimal refinery Impact: <1%
- Additional GHG reductions for ethanol impact depends on ethanol source

✓ Efficiency-ethanol combined GHG reductions ~ 30% for cellulosic ethanol with E40!

The EPA R Factor Equation Is Used to Adjust *Measured* Fuel Economy for CAFE Compliance

$$MPG = \frac{(5174 * 10^4 * CWF * SG)}{[((CWF * HC) + (0.429 * CO) + (0.273 * CO_2)) * ((0.6 * SG * NHV) + 5471)]}$$

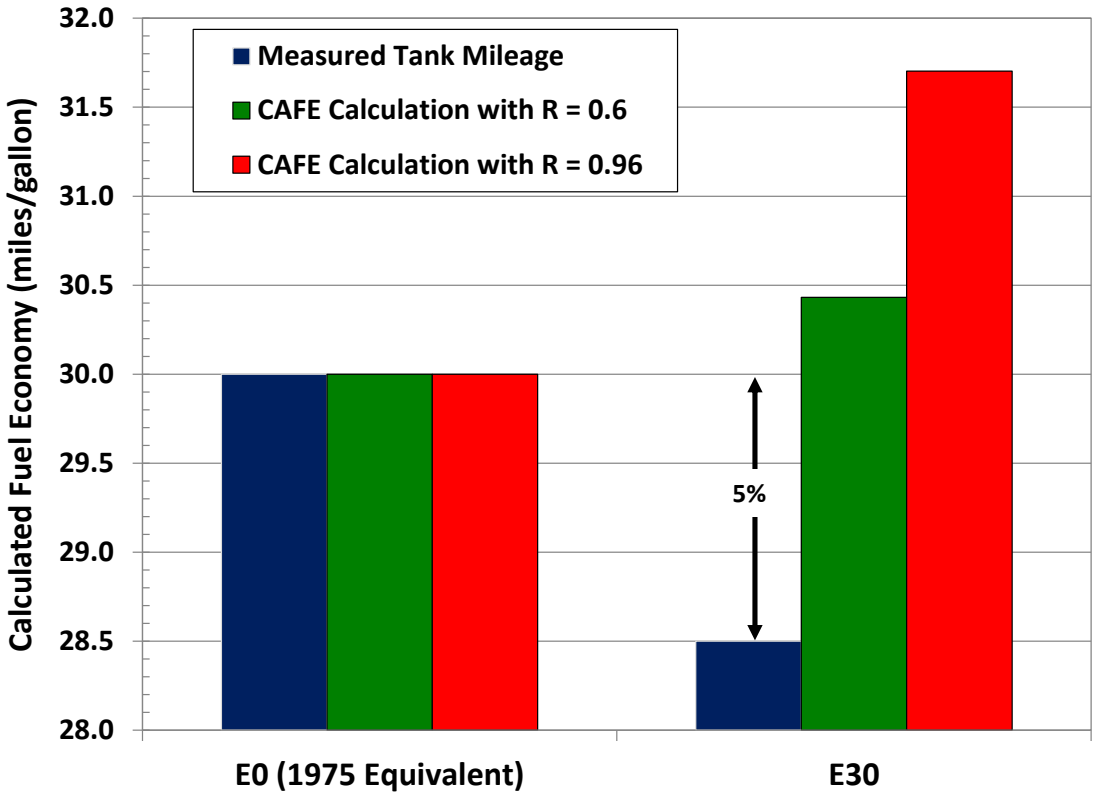
code of federal regulations

This is "R"

- Corporate Average Fuel Economy (CAFE) has been regulated since 1975
- "R" equation relates *measured* fuel economy back to 1975 E0 reference fuel (certification fuels have always been E0)
- Tier 3 requires E10 certification fuel beginning in 2017
- High Octane E20-E40 certification blend will be even more dependent on an updated R Factor

EPA "R Factor" To Be Revised for Ethanol-blended Fuels for Fuel Economy Certification

- R is currently 0.6.
- Recent publications suggest that R should be ~0.96 for today's vehicles.
- Manufacturers will have limited incentive to certify on lower energy density fuels if R remains at 0.6.



Example for illustrative purposes. Arbitrary 30 mpg base E0 FE, arbitrary assumption that equivalent vehicle with future high compression, downspeeded engine achieves 28.5 mpg.

- **With correct R Factor, high-octane mid-level blends can offer real CAFE as well as GHG benefits.**

Just for fun

World's Fastest Car is a Flex Fuel Vehicle

- **Koenigsegg One:1**
  - "one-to-one"
- **5.0 liter turbo V8**
- **1341 hp with E85**
  - 1161 hp with pump gasoline

Koenigsegg

Zero to 60 mph: 2.5 sec
Zero to 100 mph: 4.5 sec
Standing ¼-mile: 9.0 sec
Top speed: 273 mph

http://www.koenigsegg.com/wp-content/uploads/Koenigsegg_2014_One1.pdf
http://www.caranddriver.com/reviews/2015-koenigsegg-one1-first-drive-review