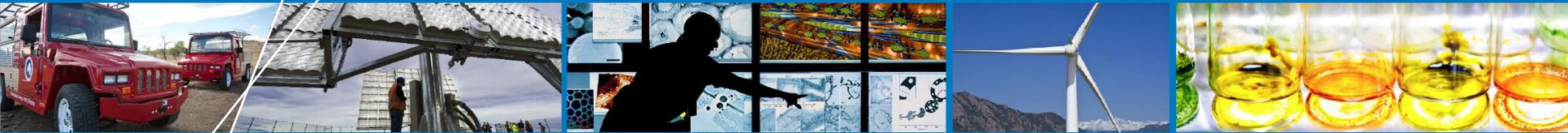


High Octane Fuels: Benefits and Challenges



Presenter: Robert L. McCormick

March 17, 2016

Increasing Biofuel Deployment through use of High Octane Fuels

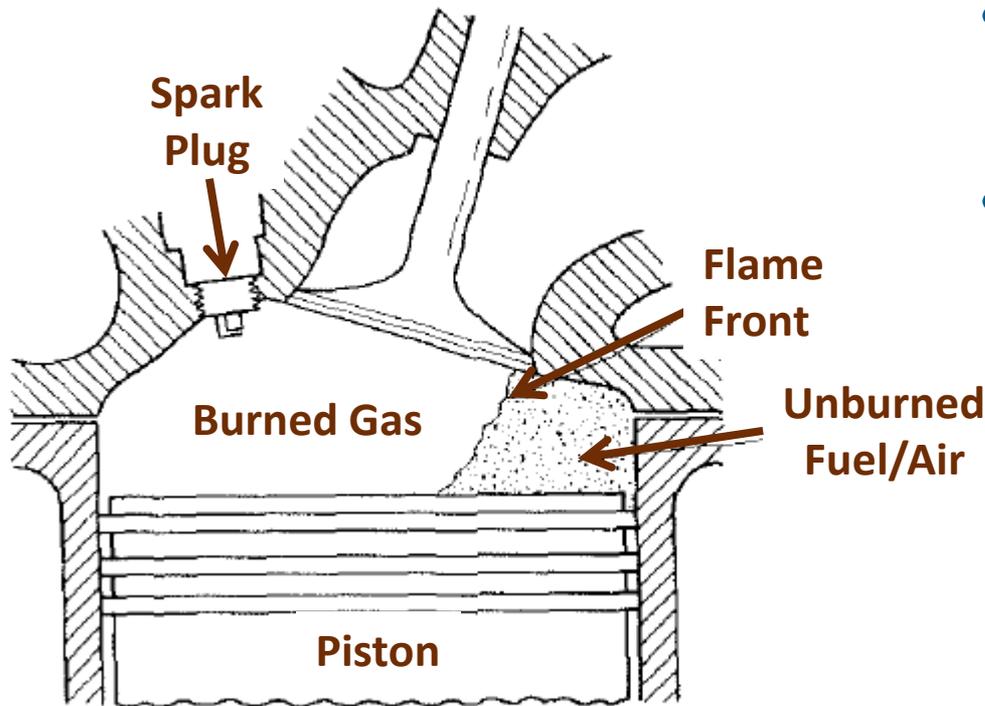
Multi-Lab Team (NREL/ANL/ORNL)

Explore Benefits/Challenges of New High-Octane Mid Level Blend
(USDOE - Bioenergy Technologies Office)

- Quantification of knock resistance properties and low-cost blendstocks (NREL)
- Fuel economy potential in dedicated vehicle (ORNL)
- Infrastructure compatibility (NREL & ORNL)
- Market analysis (NREL & ORNL)
- Well-to-wheels analysis (ANL)

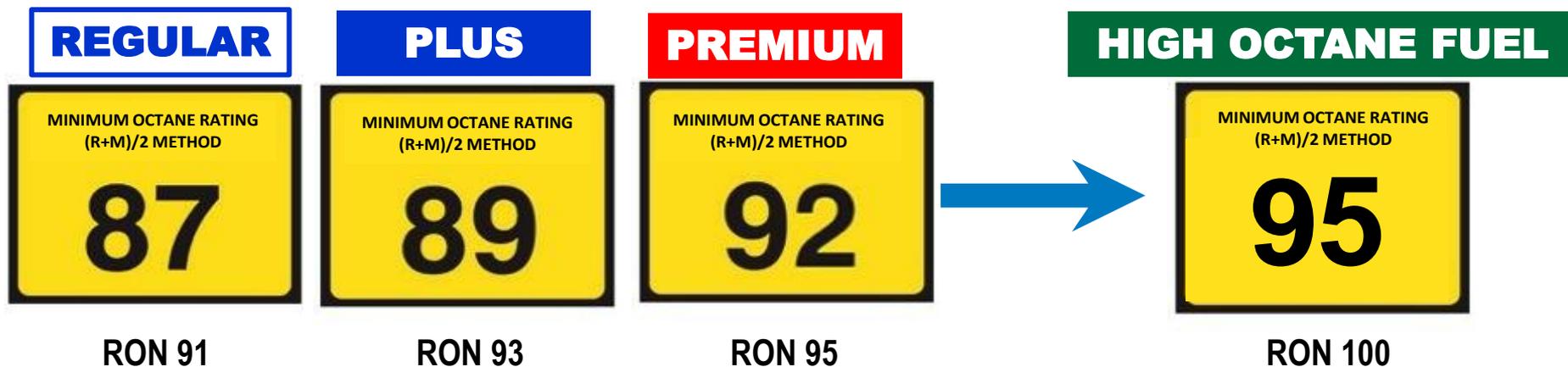
What is Engine Knock?

- Fuel with adequate octane number is required to prevent engine knock
- Knock occurs when unburned fuel/air mixture auto-ignites – essentially a small explosion in the engine
 - Higher octane fuel is more resistant to auto-ignition



- Knock can cause engine damage
- Modern cars have knock sensors
 - Reduce engine power and efficiency at knock onset
 - Drivers rarely experience knock

What is Octane Number?



- **Pump octane is the average of research octane (RON) and motor octane (MON) – also known as $(R + M)/2$**
 - Two tests to cover the full range of engine operating conditions 80 years ago when this was introduced
- **For modern technology engines, RON is the better measure of performance (knock prevention)**
- **There is no nationwide (ASTM) standard for minimum octane number in the United States**

High Octane Fuel: Key to High Efficiency Engines

Strategies to Increase Engine Efficiency (Lower GHG Emissions):

1. Increased compression ratio

- Greater thermodynamic efficiency

2. Engine downsizing/downspeeding

- Smaller engines operating at low-speed/higher load are more efficient
- Optimized with 6 to 9 speed transmission

3. Turbocharging

- Recovering energy from the engine exhaust
- Increase specific power allowing smaller engine

4. Direct injection

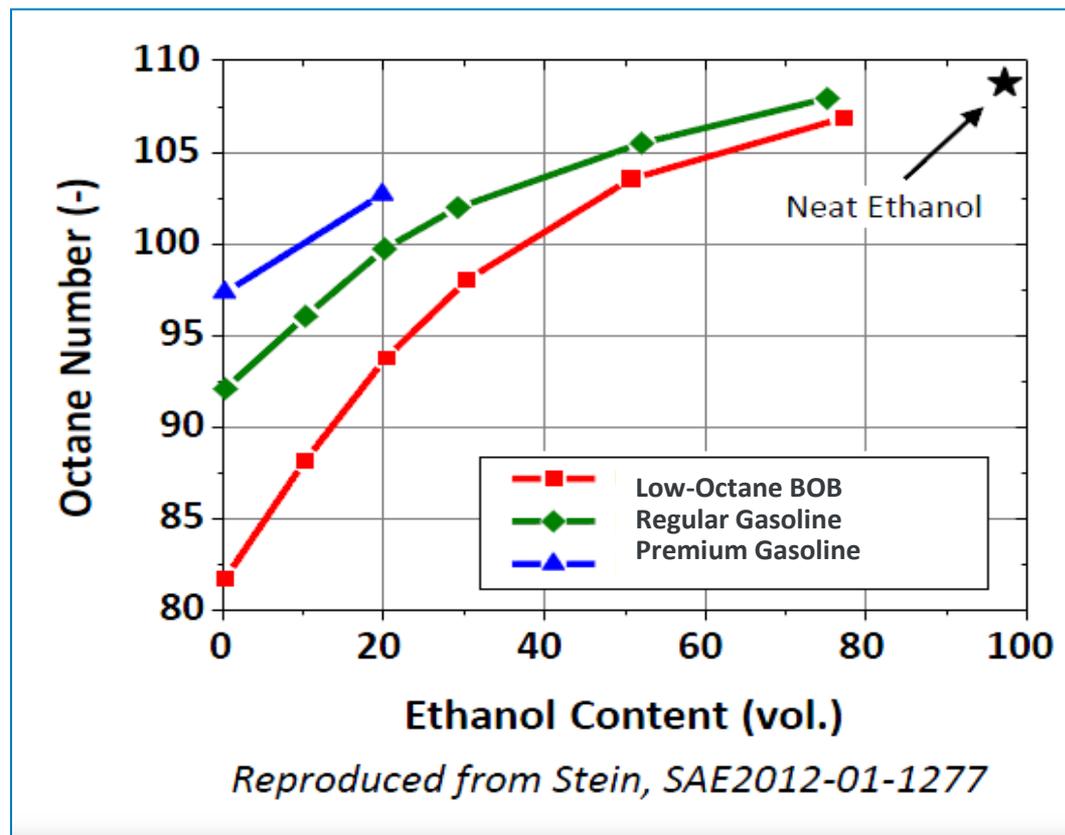
- Fuel evaporates in the combustion cylinder, cooling the air-fuel mixture

All of these strategies can take advantage of ethanol's high knock resistance:

- *Higher octane (1, 2, and 3)*
- *Higher heat of vaporization (4)*

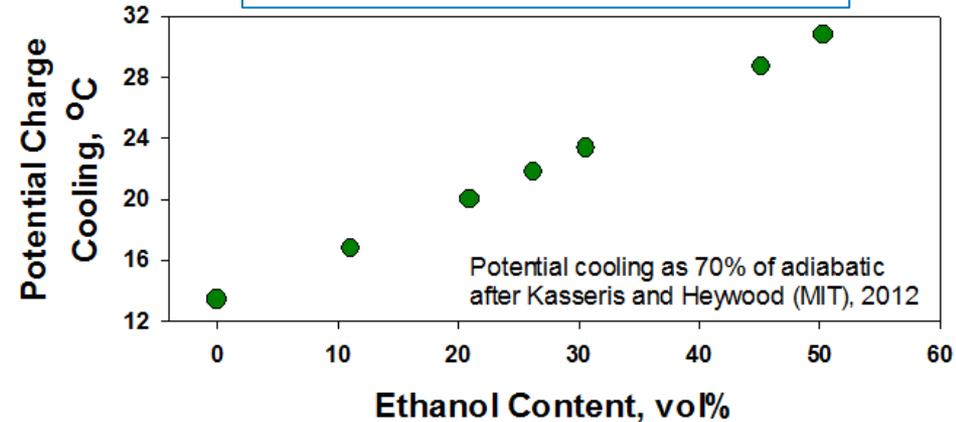
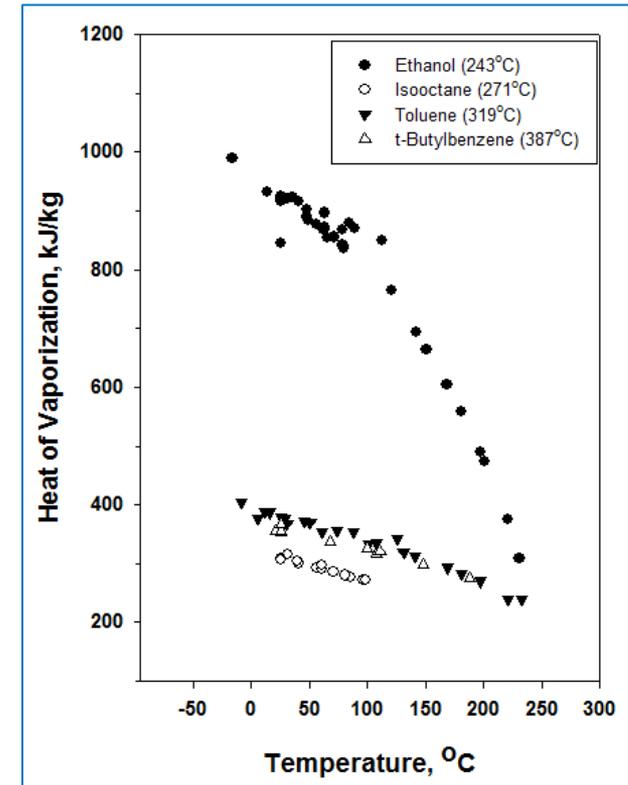
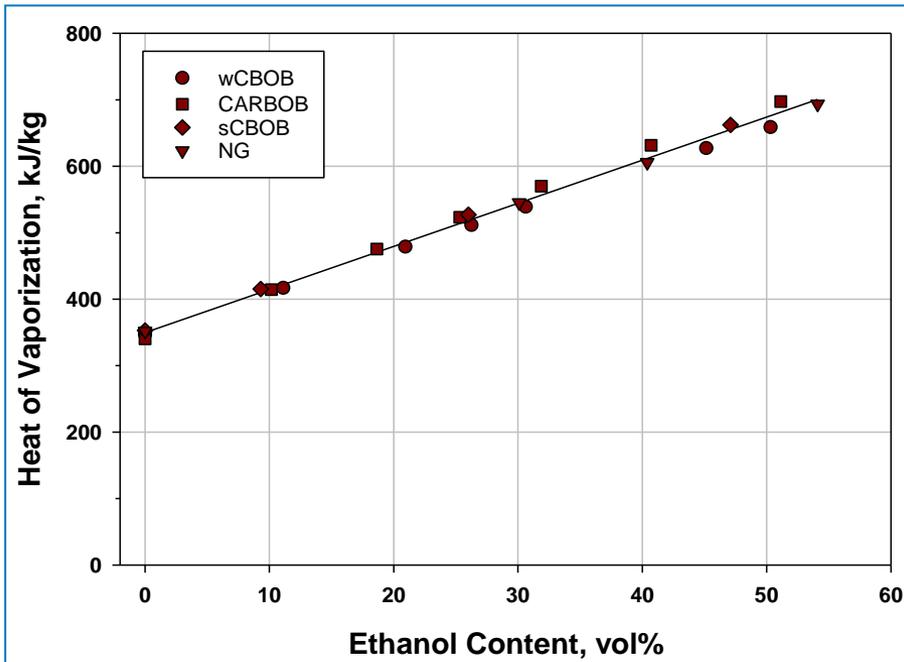
Ethanol's Impact on Octane Number

- Ethanol is an octane booster
- Non-linear influence of ethanol content → most benefit at lower levels
- Optimum blend likely 20-40% ethanol



Ethanol and Charge Cooling

- Ethanol almost 3x higher heat of vaporization than gasoline
- MIT study suggests 1 RON unit increase for every 3°C additional cooling



What is needed for a high efficiency engine?

High Octane Fuel (HOF) will likely be:

- **RON of 98 to 100 (note some premium gasoline today has a RON of 98)**
- **25-40% ethanol for charge cooling, fossil carbon displacement**

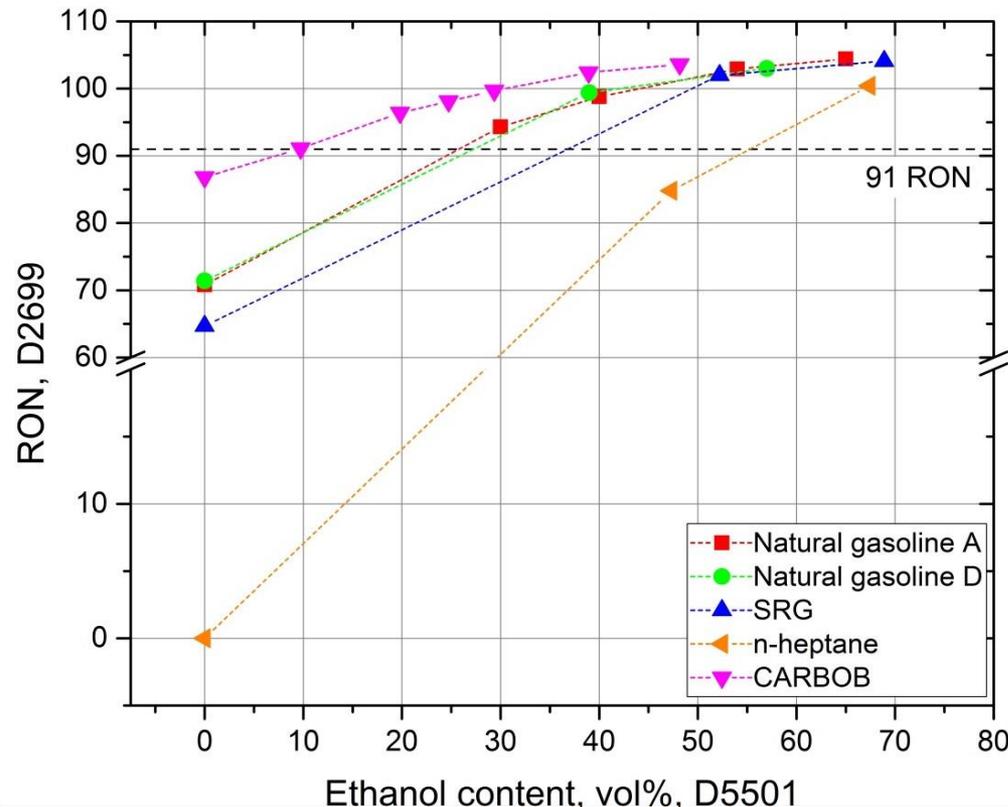
Goal is Volumetric Fuel Economy Parity:

- **E25 vs E10 is ~ 5% efficiency gain**
- **E40 vs E10 is ~10% efficiency gain**

Energy density penalty is linear with ethanol concentration, power and efficiency gains are non-linear

Low-Cost Blendstocks (Natural Gasoline)

- Because of high octane number of ethanol a lower cost blendstock may be used
- Natural gasoline, a byproduct of natural gas production:
 - Dramatic recent increase in production – roughly 1.5 billion gal 2014
 - Cost significantly less than conventional gasoline (\$0.70/gal recently)
 - High vapor pressure – advantage for blending with high levels of ethanol
- **RON of 100 nearly achieved in NG at E40**



- Vapor pressure acceptable for winter blend
- For summer HOF a mixture of conventional gasoline and NG likely required
- Care must be taken to meet finished fuel sulfur and benzene limits
 - D8011 - 16 Standard Specification for Natural Gasoline as a Blendstock in Ethanol Fuel Blends or as a Denaturant for Fuel Ethanol – soon to be published

Vehicle Fuel Economy Benefits

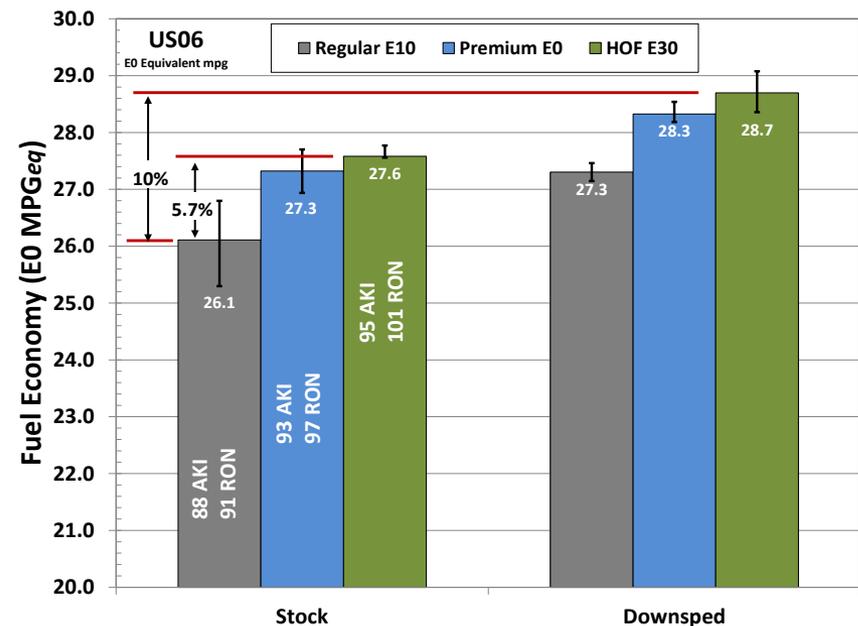
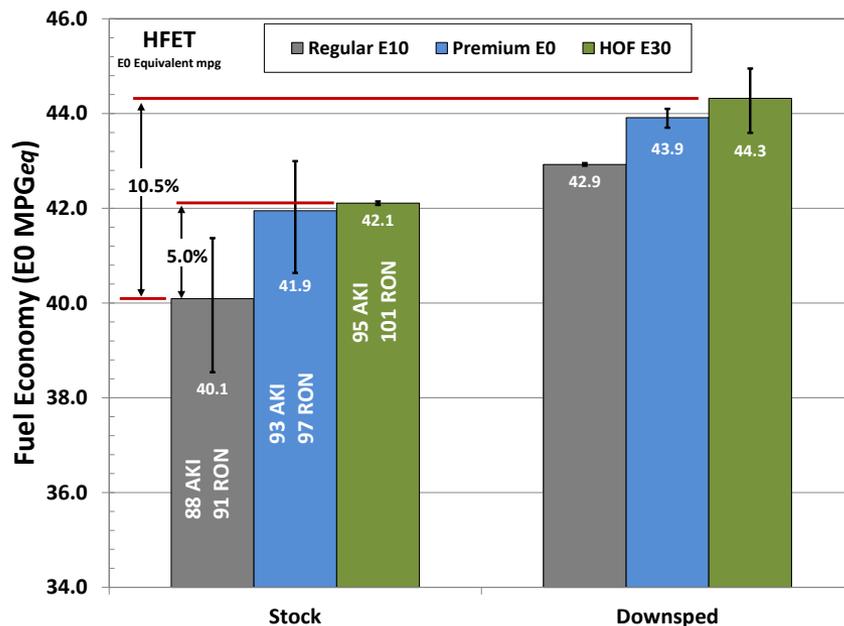
Proof of Concept

Courtesy of Oak Ridge National Laboratory

Fuel Economy Goals are Feasible

- **Goal: Volumetric Fuel Economy Parity:**
 - E25 vs E10 requires ~ 5% efficiency gain
 - E40 vs E10 requires ~10% efficiency gain
- **Sedan with 2.0 liter turbocharged, direct-injection engine**
 - Stock: 101 RON E30 demonstrated 5% gain
 - Downspped: 101 RON E30 demonstrated 10% gain
- **Requires high RON fuel, modern engine capable of adjusting phasing, and downspped vehicle**

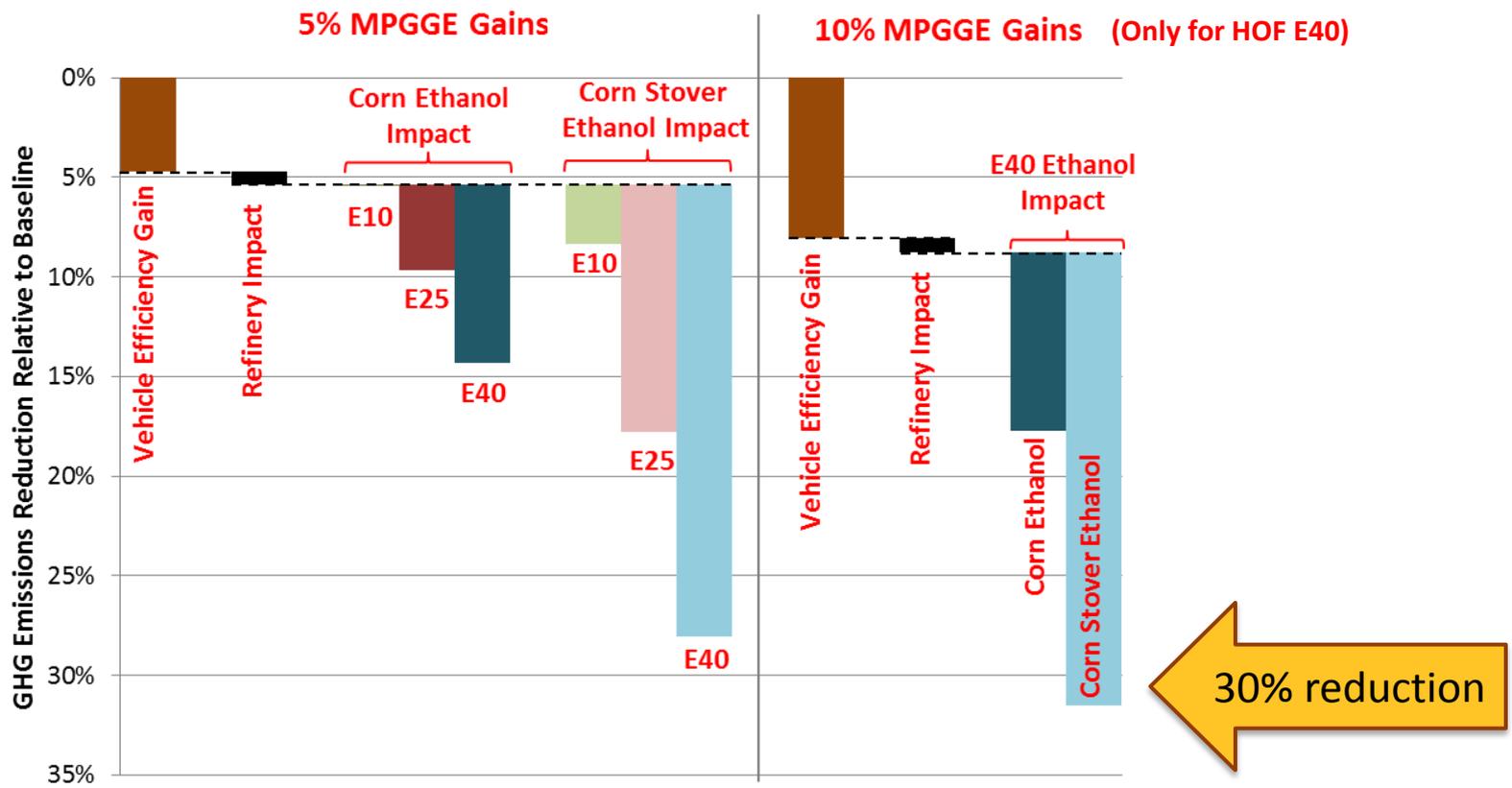
- Fuel Economy normalized to E0 equivalent basis
- Factory compression ratio
- Rear axle and drive wheel change reduces engine speed ~20%



Bottom Line: Well-to-Wheels Greenhouse Gas Emission Benefits

Courtesy of Argonne National Laboratory

HOF Reduces Well-to-Wheels Greenhouse Gas (GHG) Emissions



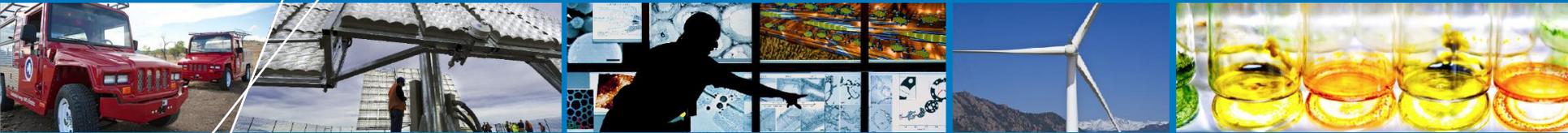
- Reductions by HOFVs fueled by HOF relative to regular gasoline (E10) baseline vehicles on per-mile basis
- GHG reductions due to efficiency gains: 5-8% respectively
- Minimal refinery Impact: <1%
- Additional GHG reductions for ethanol depends on ethanol source and blending level
- ✓ Efficiency-ethanol combined GHG reductions ~ 30% for cellulosic ethanol with E40!

Summary

- Ethanol blended at 25 to 40% provides high octane number and fuel/air charge cooling
- HOF enables design of more efficient engines
- **WTW GHG emission reductions range from 9-19% for corn ethanol HOF and 15-33% for cellulosic ethanol HOF**



High Octane Fuels: Infrastructure Assessment



Kristi Moriarty

Senior Analyst

National Renewable Energy Laboratory

March 17, 2016

Clean Cities Webinar

Retail Stations

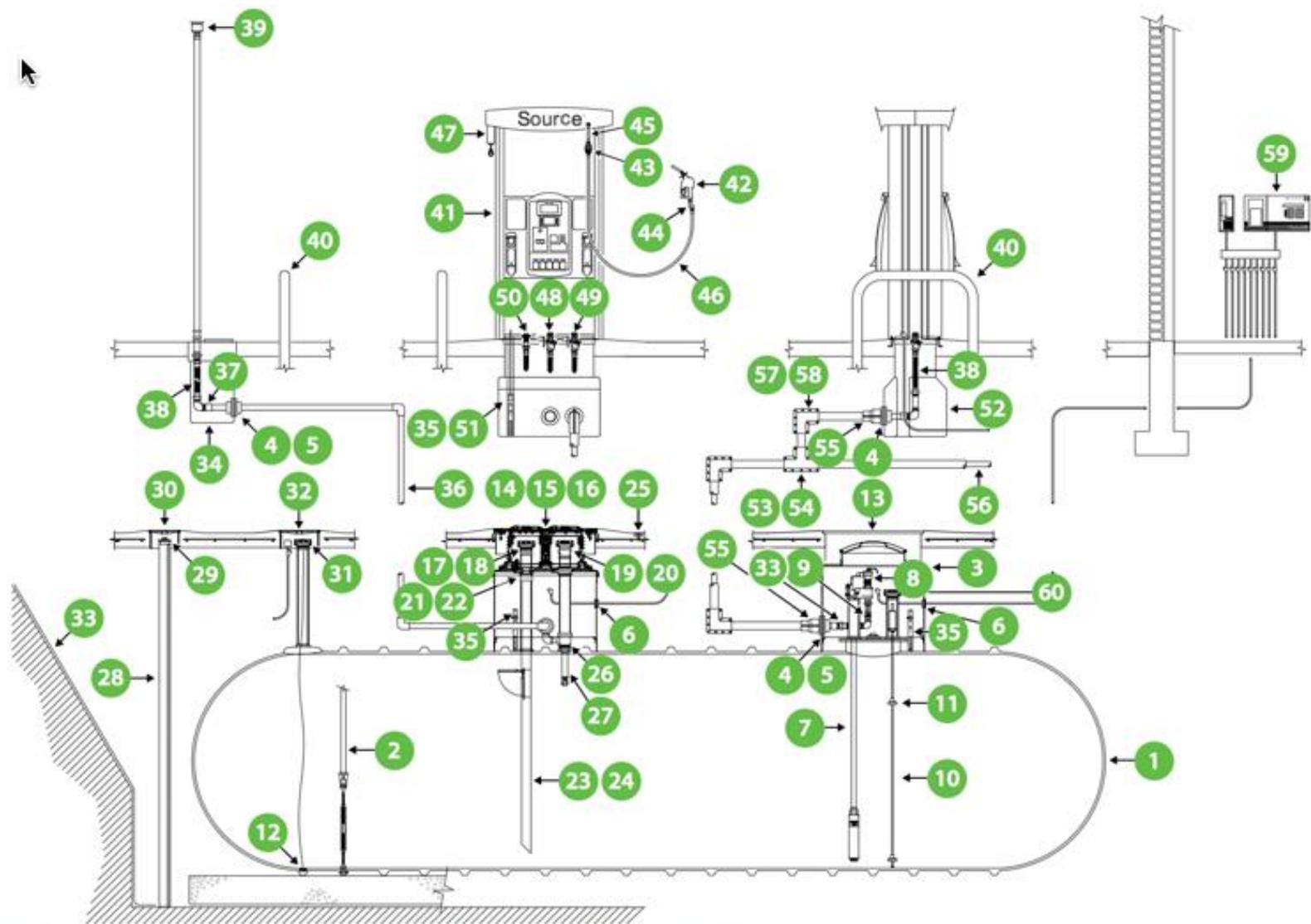


Figure 2. Typical Fuel Dispenser and Underground Storage Piping. Illustration by Source North America

Retail Stations

- **Opportunities**

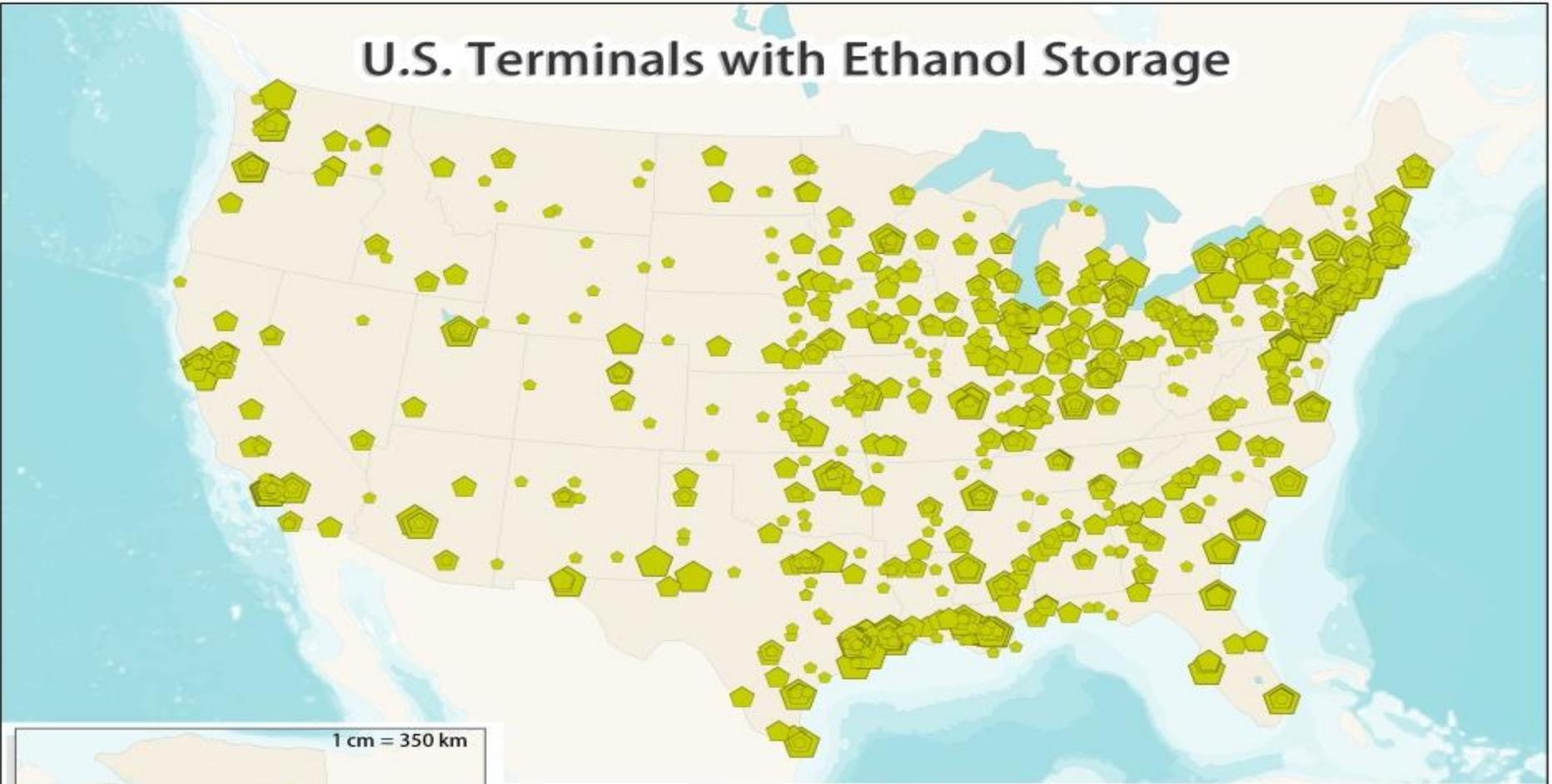
- UL E25 and E85 equipment available
- Letters stating compatibility with existing equipment with E10+ available from many manufacturers per federal UST code (updated July 2015)
- USDA BIP program will result in \$210 million more in infrastructure in 2016-these station could potentially offer an E25 or E40 fuel
- Many dispensers being replaced between now and 2017 to allow chip and pin credit cards; an opportunity to deploy more E25 and E85 equipment

Retail Stations

- **Barriers:**
 - Stations may not have equipment records necessary to meet federal compatibility requirements
 - Some equipment upgrades are necessary and station profits are small
 - E25 equipment is less expensive than E85
 - Stations with existing compatible tanks would need to decide which fuel to stop storing to accommodate an ethanol fuel

Fuel Terminals

U.S. Terminals with Ethanol Storage



1 cm = 350 km



Source: Petroleum Terminal Encyclopedia. OPIS/STALSBY 26th Edition. August 2015.

This map was produced by the National Renewable Energy Laboratory for the Department of Energy.



By: Meghan Mooney
August, 2015

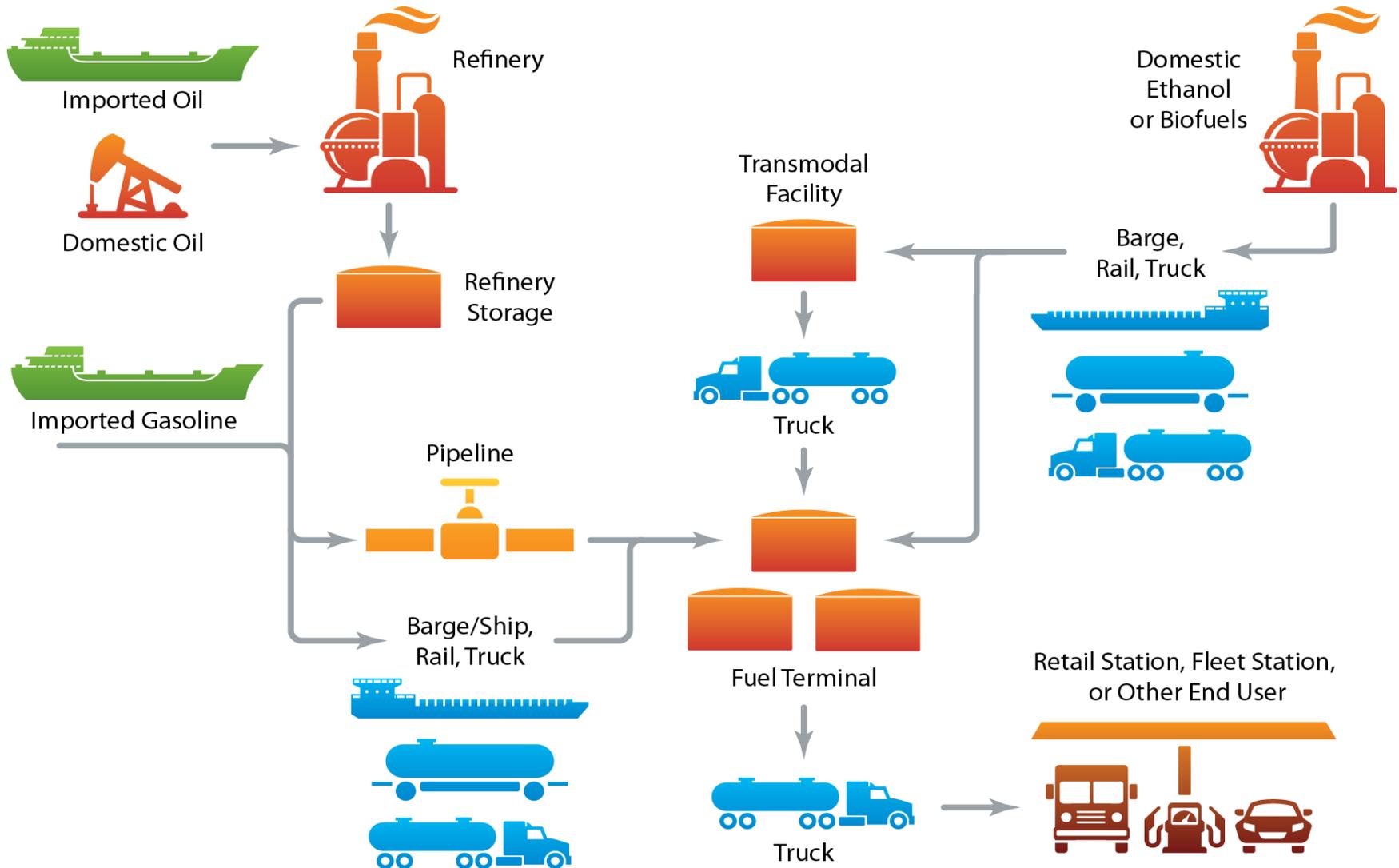
Coordinate System: NAD 1983



Storage Capacity
Millions of Barrels



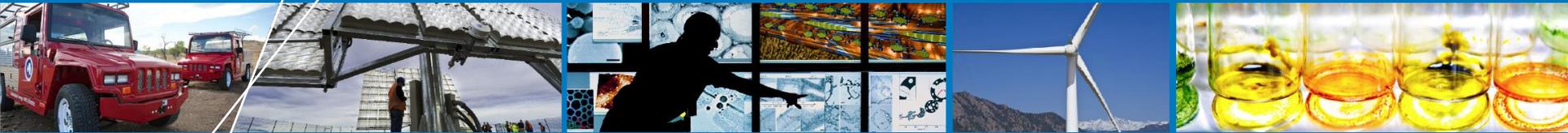
Fuel Terminals



Terminals-Ability to Store More Ethanol

- **No technical issues**
- **Several significant practical issues**
 - Nearly all tanks are in-use
 - Pipeline companies own majority of capacity and their tanks are leased to customers
 - Land availability for additional unloading facilities and tanks if needed
 - Lengthy process to change EPA operating permit to add more tanks
 - Ability for location to handle increased truck traffic for ethanol deliveries

High Octane Fuels: Market Assessment



Caley Johnson

Transportation Market Analyst

National Renewable Energy Laboratory

March 17, 2016

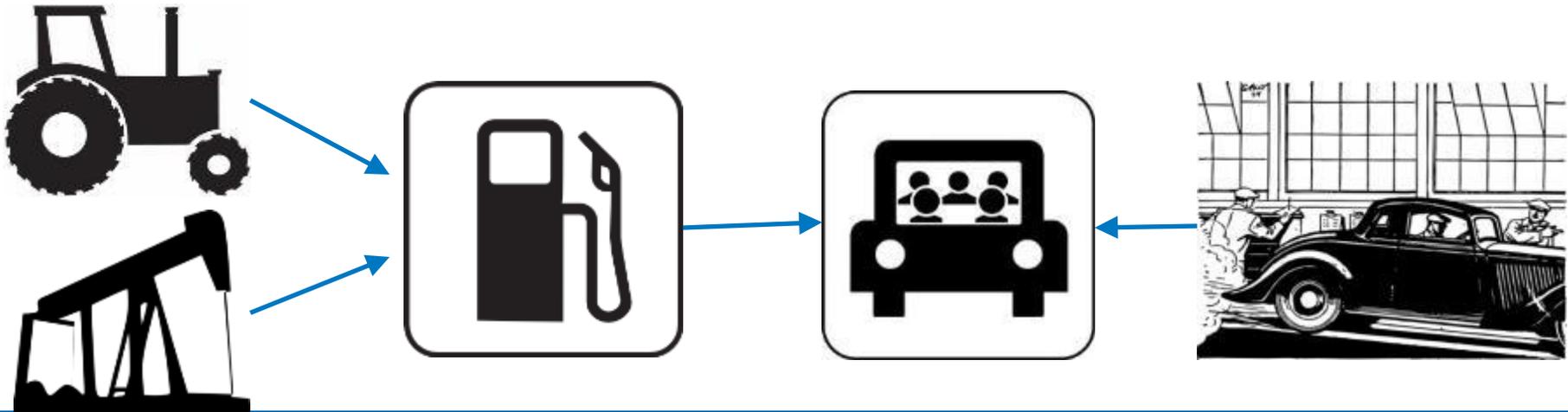
Clean Cities Webinar

Market Assessment Methodology

Purpose: Assess the feasibility, economics, and logistics of adopting HOF (E25-40) by drivers, vehicle makers, fuel retailers, and fuel producers

Strategy:

1. Identified potential benefits of High Octane Fuel (HOF) to key participants
2. Defined barriers to HOF adoption
3. Proposed strategies to curtail barriers
4. Grouped compatible/synergistic strategies into 8 adoption scenarios
5. Modeled vehicle adoption rates for various scenarios
6. Modeled biofuel production and supply chain



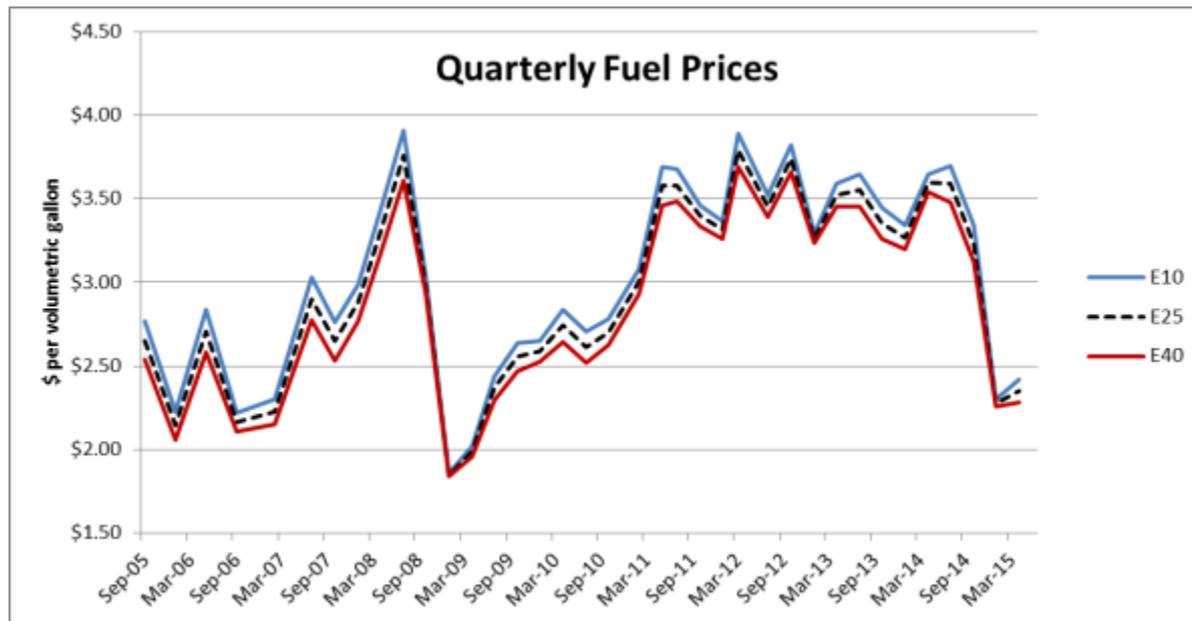
Potential Benefits of HOF Adoption

- **Drivers**

- Fuel cost savings: 8¢/gal (for E25) and 16¢/gal (E40) *past decade*
 - EIA AEO 2014 projects savings of 18¢/gal (E25) and 36¢/gal (E40) in 2030
- Reduced price volatility
- Increased torque in performance applications
- Energy security and environmental attributes

- **Vehicle manufacturers**

- Greenhouse gas (GHG) reductions
- Increased torque in performance applications



Source: Calculated from Clean Cities Price Reports by proportionally mixing E10 and E74

Potential Benefits of HOF, *continued*

- **Fuel Retailers**

- HOF could fetch higher margins in less price-competitive market
- HOF could differentiate stations in a uniform market
- Cheaper fuel could result in 3% increase in trips to convenience store*

- **Fuel Producers**

- Renewable Fuel Standard compliance
- Economies of scale for cellulosic ethanol
- Enable less expensive blendstocks
- Facilitate additional gasoline export



Source: www.usatoday.com

*Based on elasticity of demand of -0.31 and projected 9% discount in fuel price. Elasticity taken from Havranek, T., Irsova, Z., & Janda, K. (2012). Demand for gasoline is more price-inelastic than commonly thought. *Energy Economics*, 34(1), 201-207.

† Higgins, T. (2014). "Octane Number Outlook." Presentation to the 2014 SAE High Octane Fuels Symposium.

Barriers and Curtailment Strategies to HOF Adoption

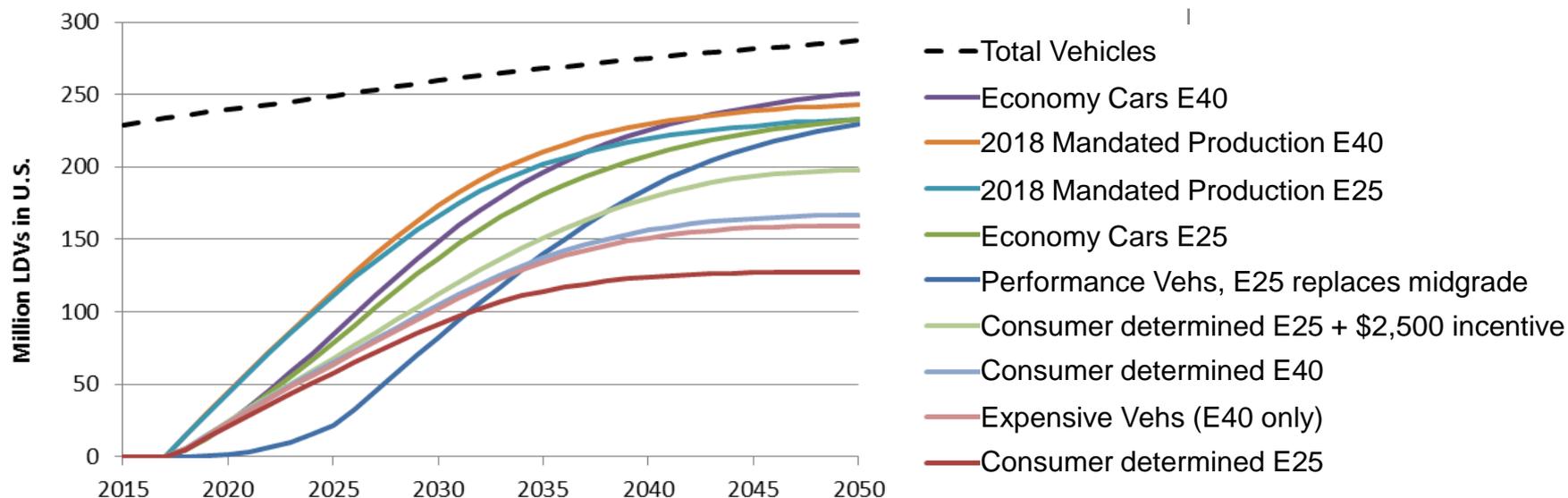
30 barriers and 94 potential curtailment strategies identified, categorized, and discussed

Tracking #	Barrier	Type	Drivers	Vehicle Mfrs.	Fuel Retailers	Fuel Producers
1	Level 1 hurdles (most formidable hurdles—show-stoppers if not properly addressed)					
1.1	Coordinated growth of supply and demand	Logistical	X	X	X	X
1.2	RFS: unpredictability leads to investment uncertainty	Regulatory		X	X	X
1.3	Misfueling legacy vehicles on HOF	Behavioral	X	X	X	
1.4	Emissions certification: HOF is not currently a certification fuel	Regulatory		X		
1.5	Fuel volatility regulations: volatility of E25 (with current blendstock) would be too high, and therefore illegal	Regulatory				X
1.6	Fuel registration requirements: HOF is not an EPA-registered fuel	Regulatory			X	X
1.7	CAFE Credits: Current calculation may not adequately reward HOFVs	Regulatory		X		
1.8	Retailer investment requirements: cost of upgrading a retail station to offer HOF	Economic			X	
1.9	HOF pricing: problem if HOF price exceeds the price of regular gasoline	Economic	X	X	X	X

HOF Introduction Scenarios

- 1. *Replace Mid-Grade with HOF and Market Performance Attributes.*** Stations offer regular E10, premium E15, and HOF from just two underground storage tanks. HOF introduced to high-performance vehicle models first.
- 2. *HOF-Tolerant, Premium-Optimized Intermediary.*** These vehicles can use HOF and capture much of HOF's high-octane benefits.
- 3. *Price-Driven Adoption.*** HOF vehicles are marketed to minimize the total cost of vehicle ownership. The first HOF vehicles introduced are the most efficient models, fuel retailers and vehicle purchasers are incentivized, and the lower price of ethanol relative to gasoline leads to a lower price for HOF compared to E10.
- 4. *Accelerated Deployment.*** An aggressive bookend scenario. All new vehicles are optimized for HOF beginning in 2018 and all dispensing equipment sold is HOF compatible.
- 5. *E51 Intermediary.*** HOFVs are optimized to E40 but use E51 sold through the current flex fuel infrastructure until the HOF market is large enough to support dedicated refueling.
- 6. *Blender Pumps.*** E10, E15, HOF, and flex fuel are blended from two tanks containing E0 (or E10) and flex fuel (E51-83).
- 7. *Regional Deployment.*** Resources for achieving critical mass of both supply and demand for HOF are focused on the Midwest market.
- 8. *Expensive.*** A slow bookend with expensive vehicles and retail dispensing equipment, HOF is E40.

Vehicle Adoption Modeling



- All scenarios achieved a substantial percentage (43%–79%) of the light-duty vehicle stock by 2035
- More HOFVs are adopted if HOF is E40 (vs. E25) if they offer greater fuel cost savings and GHG benefit
- \$2,500 purchase incentive boosted 2035 penetration 32% in consumer determined scenarios
- Designating certain vehicle models to be HOF-dedicated leads to higher adoption rates but early adoption speed depends on model production volumes

Market Assessment Conclusions

Results show potential for significant HOF consumption in 2035 under the scenarios modeled

- 30 billion gallons of ethanol (75 billion gallons of E40)
- Over 60% of 2035 LDV fuel market

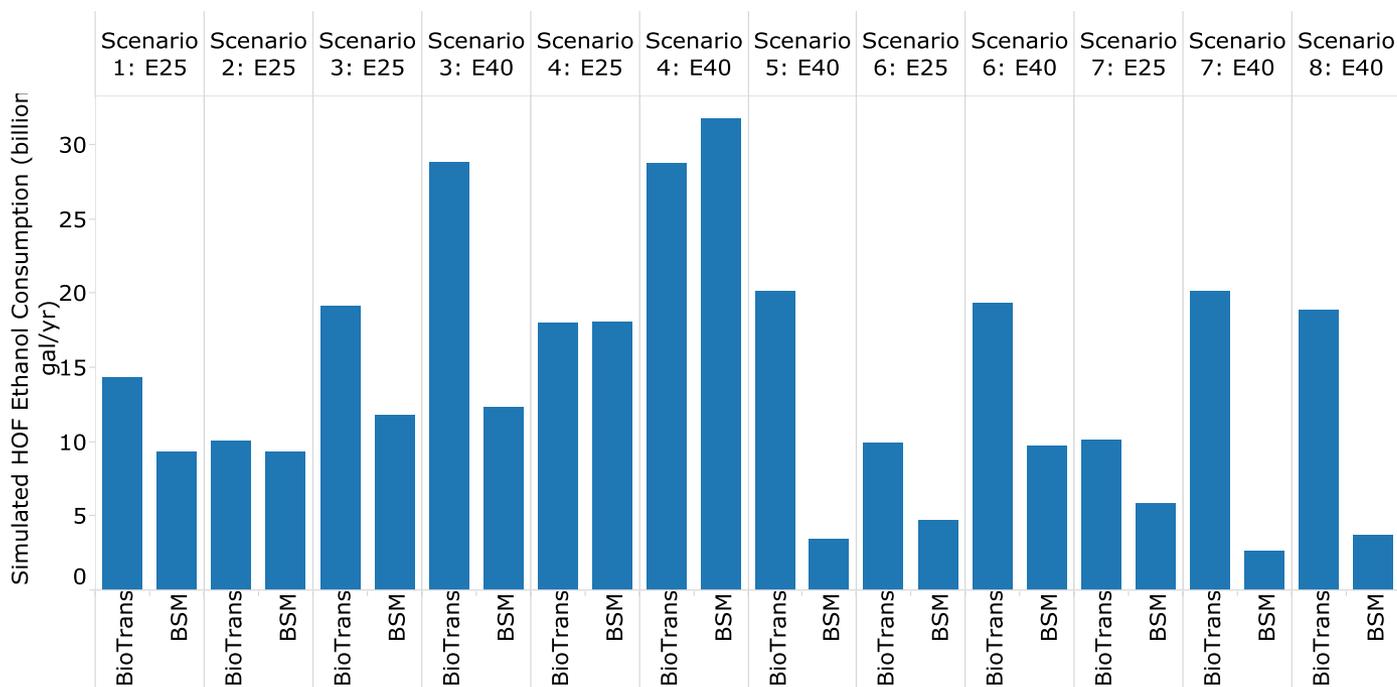


Figure 31. Comparison of the simulated HOF ethanol demand in 2035, given vehicle fleet, by scenario for the BSM and BioTrans models

The differences between the HOF ethanol demand in the two models illustrates the impact of assumptions of a short term NPV-focus (BSM) and a long term social welfare focus (BioTrans)

Conclusions, *continued*



Where are the bottlenecks?

- 1. Current regulations that have not yet addressed HOF**
 - Unless government enables HOF registration, HOF certification fuel, continues RFS, and adjusts future GHG/CAFE regulations to reward HOF
- 2. Fuel retailers' investment in HOF equipment is limiting factor in most scenarios**
 - Unless incentivized to invest, equipment cost is reduced, or if only compatible equipment is sold in advance. In which case:
- 3. Construction rate of new biorefineries is limiting factor**
 - Unless enough time passes to allow construction to catch up (circa 2025) or rate surpasses historical levels. In which case:
- 4. HOF vehicle adoption is limiting factor**
 - Only in scenarios where adequate retailer investment has been made and biorefinery construction has caught up with demand (post 2025)
- 5. Feedstock availability and cost are not the limiting factors in any scenarios**

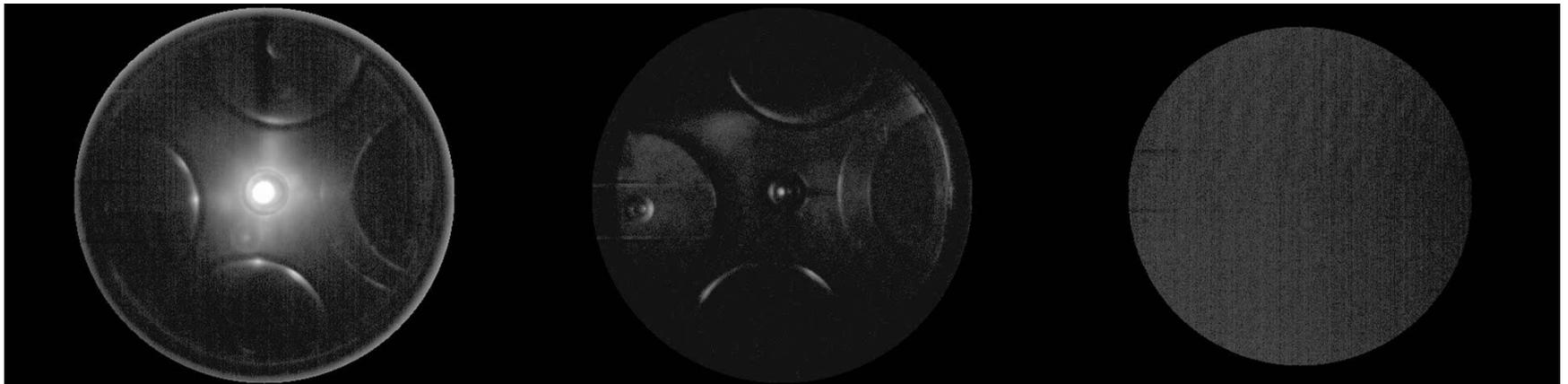
DOE's Optima Project

- **Current fuels have evolved somewhat independently from their vehicles**
- **There are better fuel/vehicle combinations available**
 - Many of them are biofuels
- **Incremental changes are expensive and imperfect**
- **DOE is searching for ideal fuel/vehicle combination for three main combustion strategies**

Spark Ignition

Kinetically Controlled

Compression Ignition



**Research supported by the United States
Department of Energy – Bioenergy
Technologies Office**

**All reports and project summary can be
found at <https://bioenergykdf.net/hof>**

**Contacts: robert.mccormick@nrel.gov.
kristi.moriarty@nrel.gov, caley.johnson@nrel.gov**