Benefits of High Octane, Mid-Level Ethanol Fuel Blends

25x'25 Webinar
June 18, 2015

25x'25 AMERICA'S ENERGY FUTURE

Bringing the Vision to Life

Welcome!

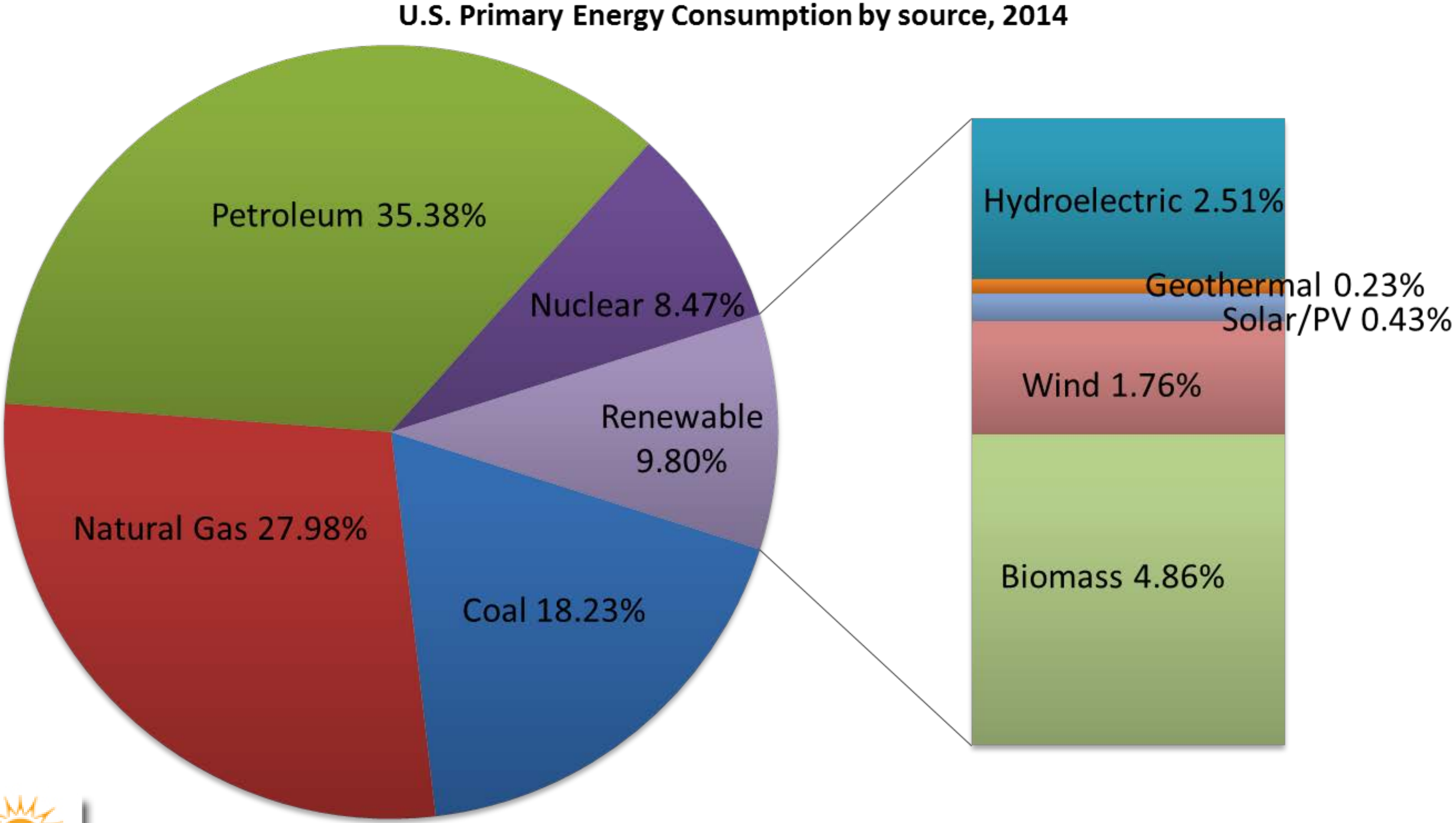
Introduction and Objectives

Ernie Shea

25x’25 Project Coordinator

Where are we now?

2014 Total Energy Consumption: 98.32 Quad BTU
2014 Renewable Energy Consumption: 9.63 Quad BTU

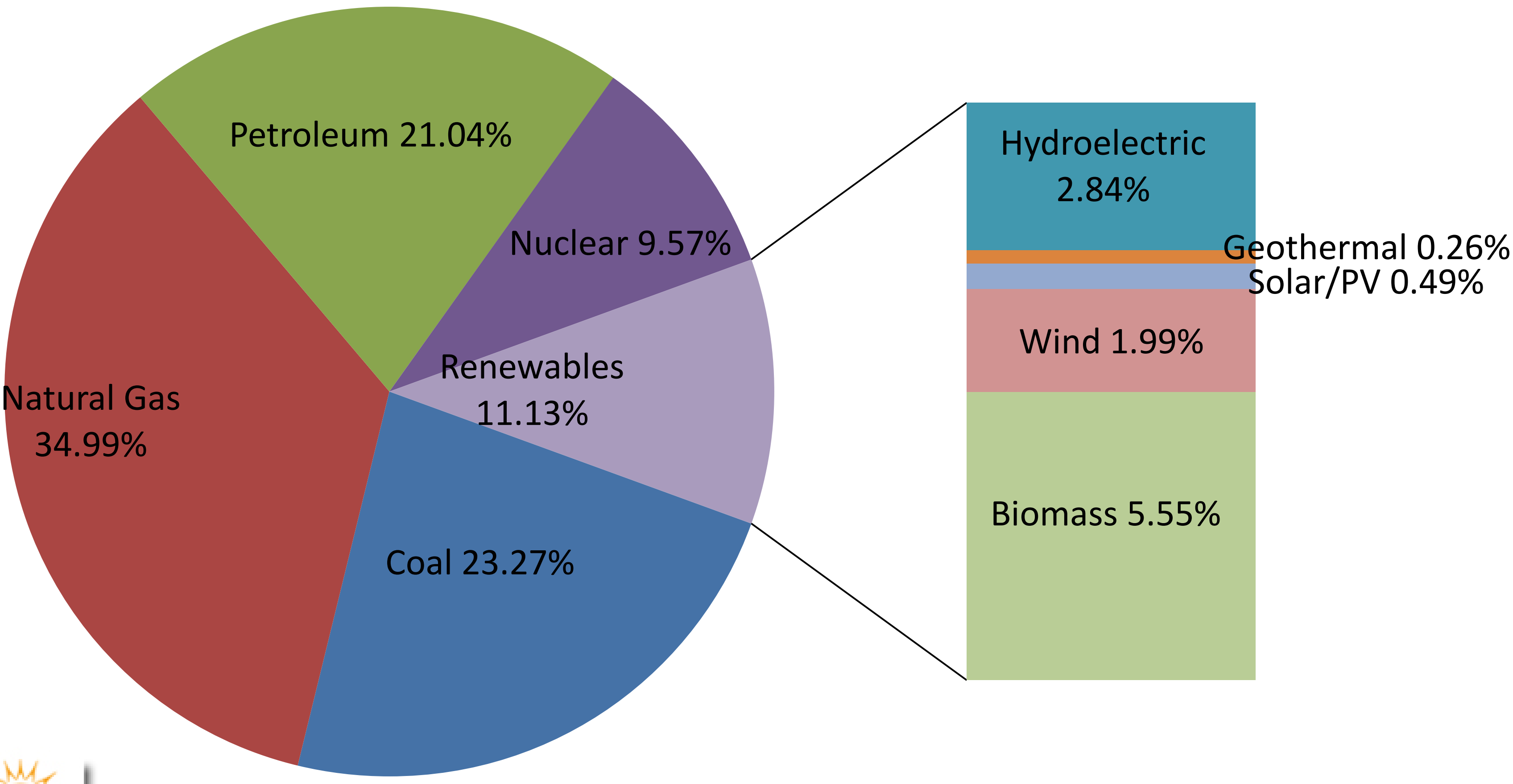


Source: U.S. Energy Information Administration

Where are we now?

2014 Total Energy Production: 87.04 Quad BTU
2014 Renewable Energy Production: 9.68 Quad BTU

U.S. Primary Energy Production by source, 2014



Source: U.S. Energy Information Administration

Webinar Objective

- Share and discuss provisional findings from coordinated DOE national laboratory studies on the opportunities and challenges associated with the deployment of high octane, mid-level ethanol blend transportation fuels.

Session Leaders

- **Ernie Shea**, 25x'25 Project Coordinator- moderator
- **Bob McCormick**, Principal Engineer, National Renewable Energy Laboratory
- **Brian West**, Deputy Center Director and Senior Development Staff Member, Oak Ridge National Laboratory
- **Michael Wang,** Senior Scientist, Energy Systems, Argonne National Laboratory
- **Tim Theiss**, Program Manager, Bioenergy Technologies Program, Oak Ridge National Laboratory

Webinar Procedures:

- Lines will be muted during presentations to minimize background noise
- For presenters and Q&A, un-mute by pressing *6
- Will take questions at the end of the presentations
- To ask a question, either press *6 to un-mute or use the chat feature to submit a written question

Increasing Biofuel Deployment through use of High Octane Fuels

DOE Lab Partners
Robert L. McCormick – NREL
Brian West & Tim Theiss – ORNL
Michael Wang – ANL

June 18, 2015

Work supported by Department of Energy
Bioenergy Technologies Office and Vehicle Technologies Office

Presentation Outline

Robert McCormick – NREL

- **Octane number, engine knock, and why you should care**
- **Ethanol and octane number**
- **Infrastructure compatibility of mid-level ethanol blends**

Brian West - ORNL

- **DOE program on high octane fuels and efficient engines**
- **Benefits in flex fuel vehicles**
- **Benefits in dedicated vehicles**

Robert McCormick – NREL

- **Potential benefits, hurdles, and resolutions of HOF to key stakeholders**
- **HOF vehicle adoption simulation**
- **Biofuel production supply chain simulation**

Michael Wang – ANL

- **Refinery analysis**
- **Well-to-wheel green house gas (GHG) & energy analysis**

Summary

Overview: Octane number, efficient engines, ethanol, and infrastructure

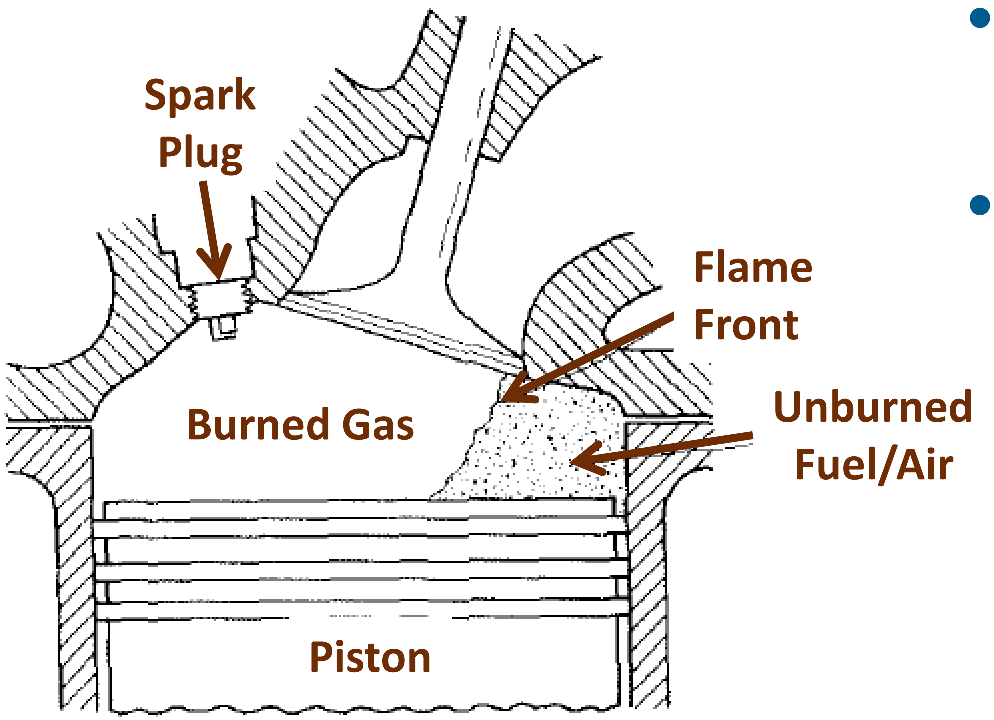
Robert L. McCormick

25x'25 Webinar Briefing
June 18, 2015

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

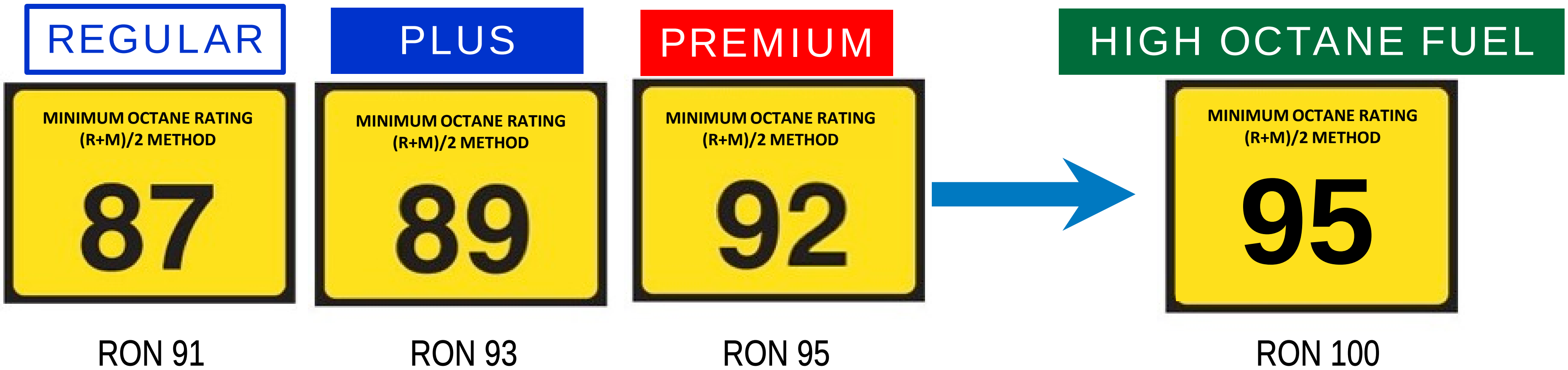
What is Engine Knock?

- **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**

Why do we care?

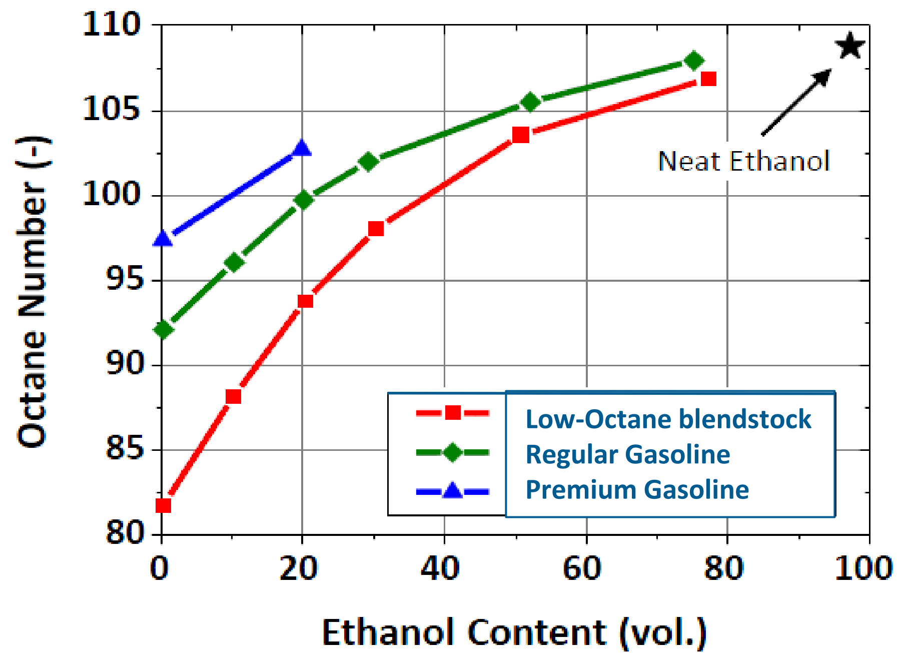
Strategies to Increase Engine Efficiency (and Lower GHG Emissions):

- **Increased compression ratio**
  - Greater thermodynamic efficiency
- **Engine downsizing/downspeeding**
  - Smaller engines operating at low-speed/higher load are more efficient
  - Optimized with 6 to 9 speed transmission
- **Turbocharging**
  - Recovering energy from the engine exhaust
  - Increase specific power allowing smaller engine
- **Direct injection**
  - Fuel evaporates in the combustion cylinder, cooling the air-fuel mixture

All of these strategies can take advantage of higher octane (more highly knock resistant) fuels

Ethanol and Octane Number

- **Ethanol has high RON**
  - RON = 109
  - Relatively low cost source of octane
- **What about charge cooling?**
  - Ethanol almost 3x higher than gasoline
  - MIT study suggests 1 RON unit increase for every 3˚C additional cooling
- **Optimum blend likely 20-40% ethanol**
  - Non-linear benefit of higher octane vs. linear decrease in energy density



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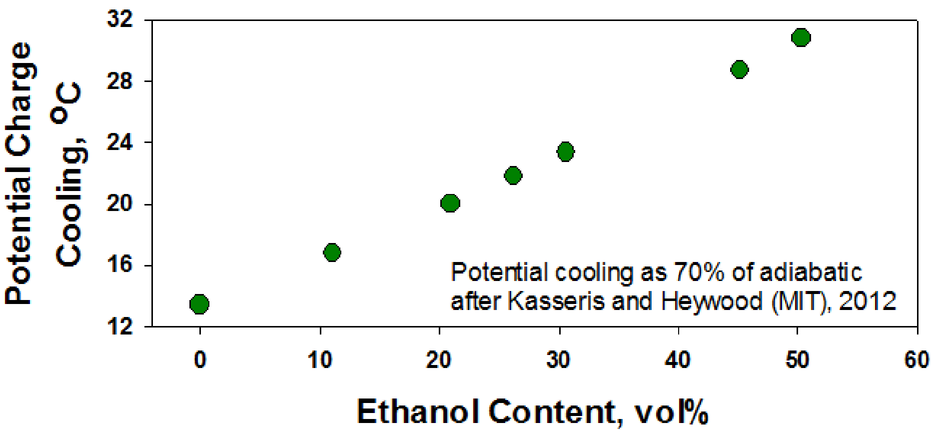


Large Challenges to New Fuel Introduction

- **EPA Requirements – Clean Air Act**
  - Emission Control Equipment Compatibility
  - Toxic Emissions and Health Effects
  - Registration
  - Misfueling Mitigation
- **Safety and Infrastructure Compatibility**
  - Prevention of Leaks
  - Fire Safety
  - Ground Water Protection
- **Engine Compatibility – Quality Standards**
  - New Vehicle Development/Deployment
  - Consumer Protection and State Fuel Quality Regulation
- **Coordinated investments in vehicles, biorefineries, and refueling infrastructure**

Joint National Lab Study

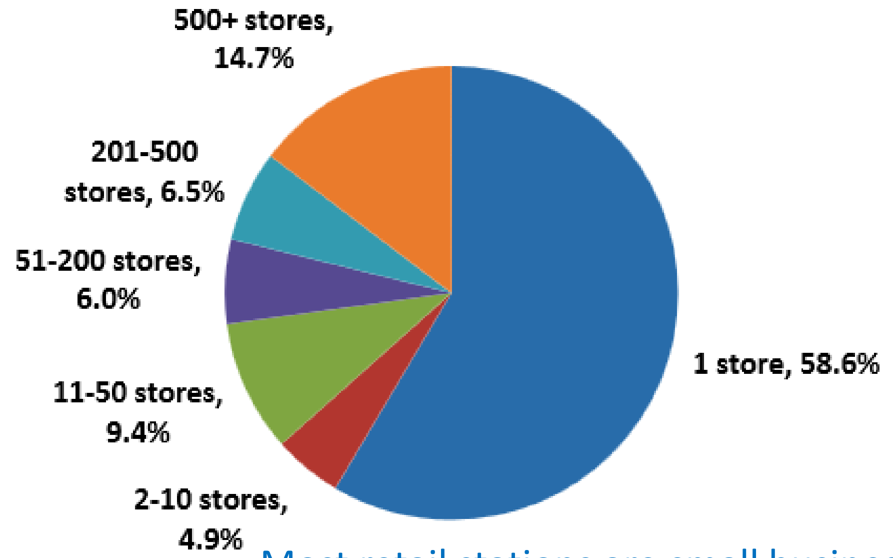
- **The potential benefits of high octane fuels (HOF) and optimized vehicles appear to be large – pump-to-wheels**
- **HOF may also create additional demand for ethanol with significant well-to-pump GHG benefits**

Three national laboratories have jointly been conducting a scoping study directed at:

- *Understanding hurdles*
- *Proposing resolutions*
- *Quantifying potential benefits*
- *Determining if additional R&D is warranted*

E20 to E40 Blends in Refueling Infrastructure

- **Most underground tanks are compatible with any ethanol blend**
- **Potential issue: refueling stations are not required to keep equipment records - a challenge to determine compatibility**
  - But can be determined by an experienced inspector
- **Fuel dispensers would have to be upgraded:**
  - Current E10 dispensers can be retrofitted to E25
  - For higher blends an E85 dispenser is required (more expensive)



Most retail stations are small businesses

Estimate that ~ 20% of stations have to carry new fuel for it to be considered convenient

High Octane Ethanol Blends for Improved Vehicle Efficiency

Brian West
Fuels, Engines, and Emissions Research Center

25x’25 Briefing
June 18, 2015

Work supported by Department of Energy
Bioenergy Technologies Office
Vehicle Technologies Office

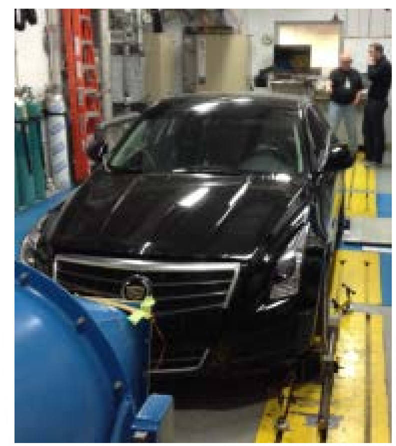
OAK RIDGE
National Laboratory

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

DOE Work supported by

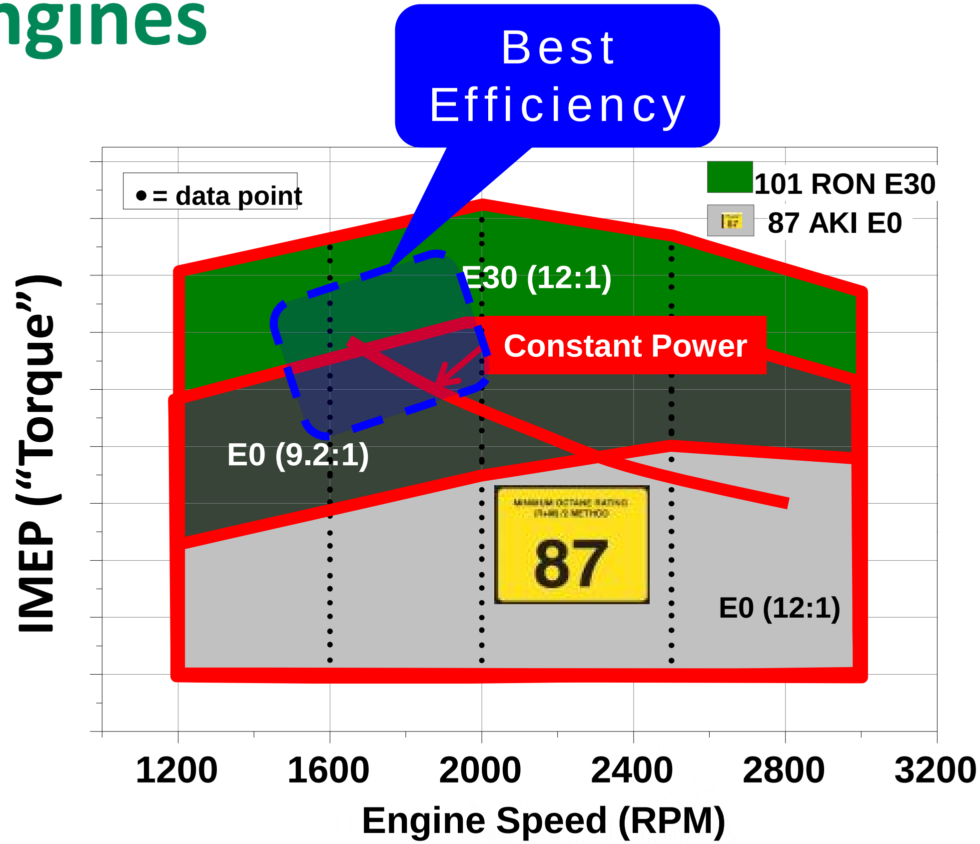
- Vehicle Technologies Office
- Bioenergy Technologies Office
- Studies quantifying
  - Infrastructure compatibility
  - Efficiency and performance improvements in engines/vehicles with high octane fuels, various sources of octane, different engine architectures
  - Market analysis
  - GHG benefits

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



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**
  - 87 pump octane E0 + 30% Ethanol = 101 RON Fuel
- **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**
- ***Every gallon of ethanol could displace a full gallon of gasoline***



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

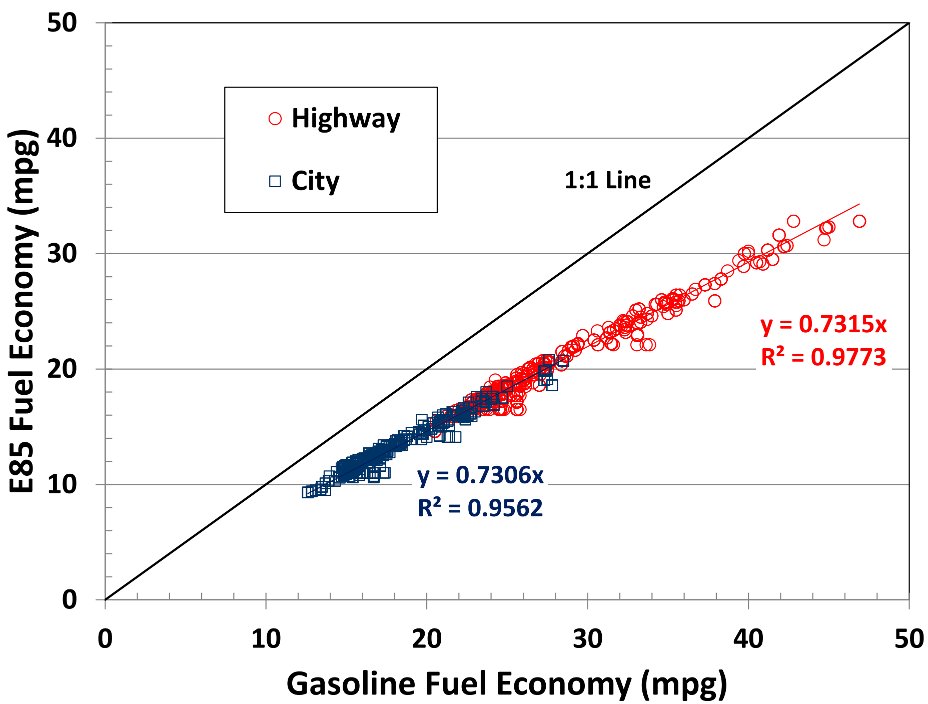
- Splitter and Szybist, ORNL

OAK RIDGE National Laboratory

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

Consumers Continue to Shy Away from "E85"

- **Over 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?"**
  – Specification allows 51% to 83% ethanol to address 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

Vehicle Study to Determine Potential Performance Improvement of Legacy FFVs with High Octane Blends

Work supported by DOE Bioenergy Technologies Office

- **Motivation: Measureable performance improvement in legacy FFVs could enable early adoption of "High Octane Fuel 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**

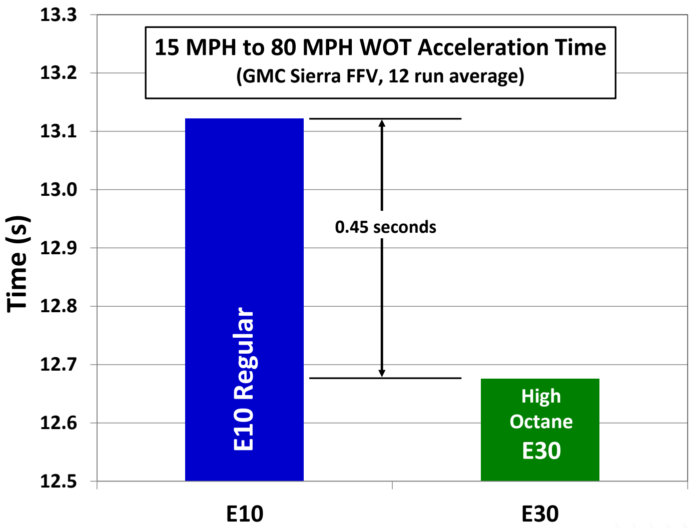
HIGH OCTANE FUEL
For your FFV

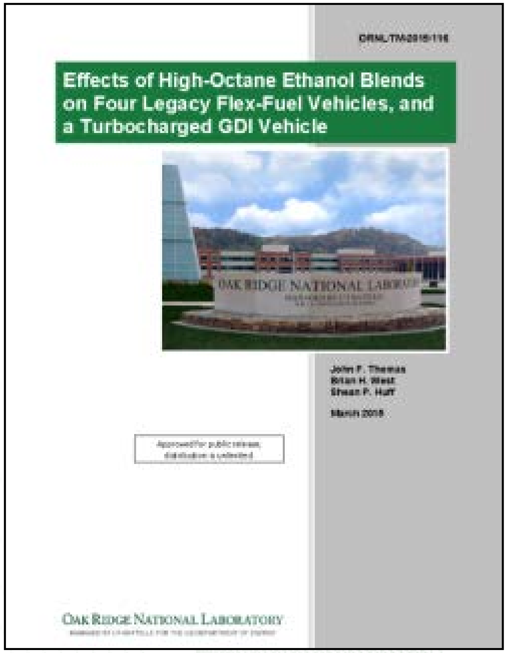
Car and Driver FFV test shows 0.4 second faster 0-60 mph time with E85

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

- **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 of all FFVs on road today filled up with E30 half the time, they would consume half-billion gallons more ethanol annually





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

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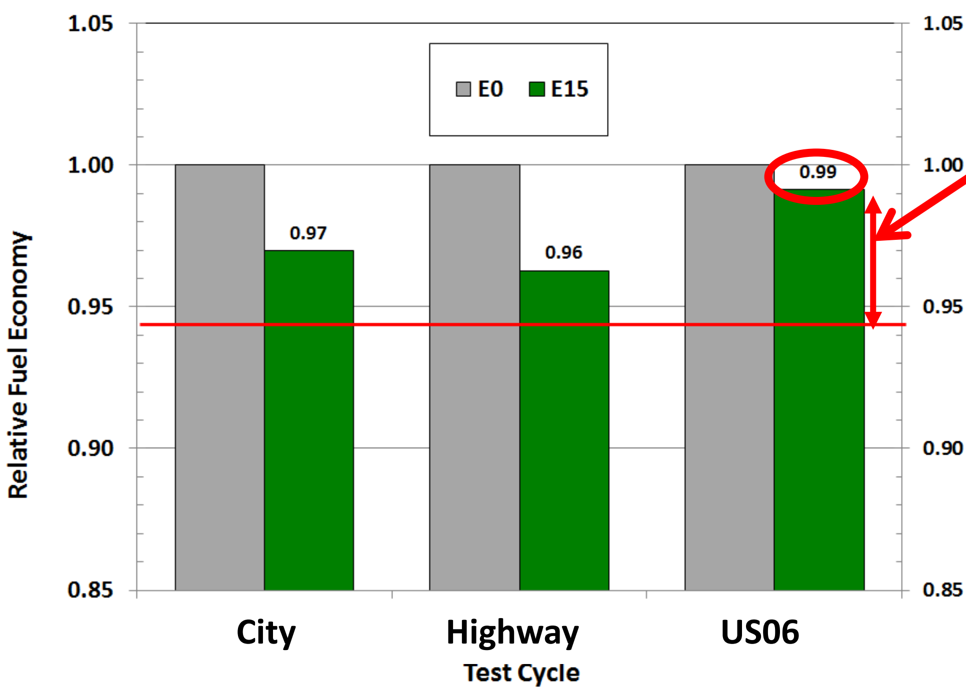
Benefits of Engine Downsizing with High Octane E-Blend Demonstrated on Late-Model Turbo Direct Injection Vehicle

- **E15-Compatible Ford EcoBoost Fiesta**
  - **1.0 liter, 3-cylinder turbo Direct Injection 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 octane E0 with 15% Ethanol**
    - **Boosts octane, lowers energy content**
  - **Test on City, Highway, and US06 (high-load cycle)**
- **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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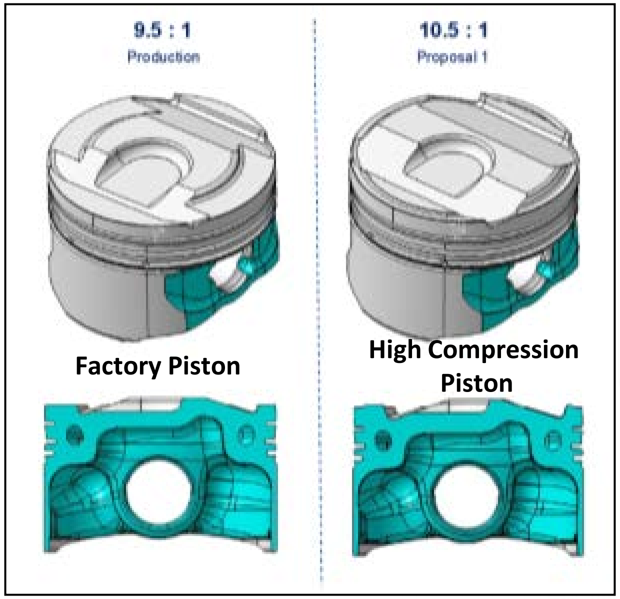
High-Octane Efficiency Benefits Demonstrated at the Vehicle Level

- **GM Cadillac ATS with 2.0 liter Turbo Direct Injection engine for dedicated vehicle study**
  - Manual Transmission and final drive gears to readily enable downspeeding
  - Currently conducting baseline tests on range of fuels with factory pistons/calibration
  - Change to high compression ratio, revise calibration
    - Pistons for high compression being designed now
  - Fuel blends will span various octane levels with different sources of octane number



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

High Octane Fuel Market Assessment

Robert McCormick

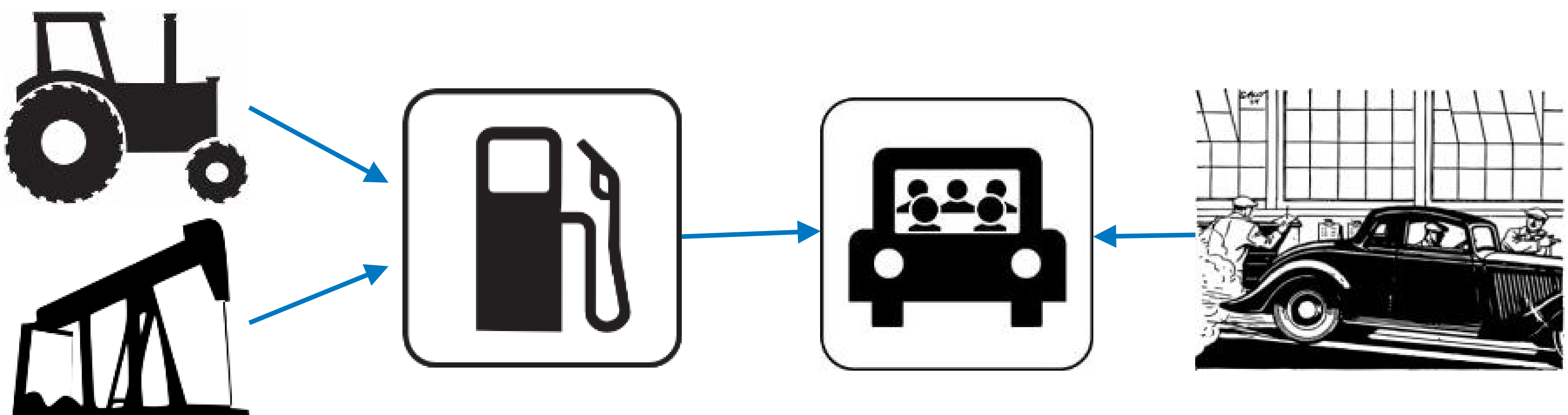
Transportation Market Analyst

High Octane Fuel Market Assessment

<u>Purpose:</u> Assess the feasibility, economics, and logistics of adopting HOF by drivers, vehicle makers, fuel retailers, and fuel producers

<u>Strategy:</u>

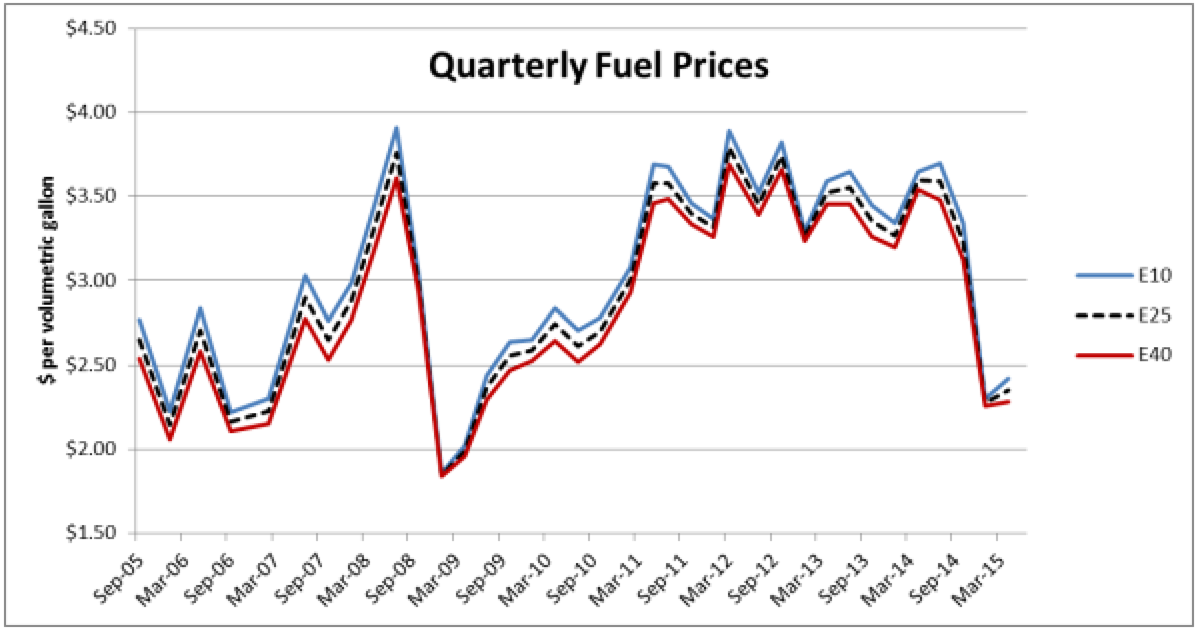
1. Identified benefits of High Octane Fuel (HOF) to key participants
2. Defined hurdles to HOF adoption
3. Proposed resolutions to hurdles
4. Grouped compatible/synergistic resolutions into 8 adoption scenarios
5. Modeled vehicle adoption rates for various scenarios
6. Modeled biofuel production and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



Potential Benefits of HOF Adoption

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

- **Vehicle manufacturers**
  - o Greenhouse gas (GHG) reductions
  - o 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*

Source: www.usatoday.com

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

*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.

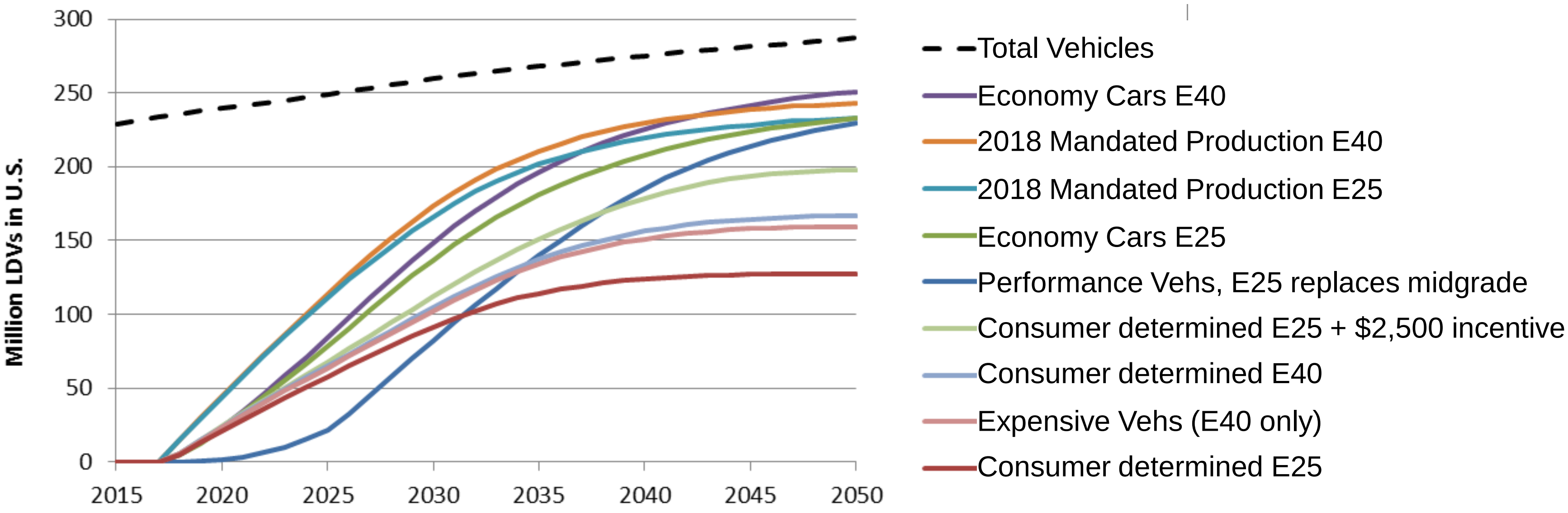
† Higgins, T. (2014). “Octane Number Outlook.” Presentation to the 2014 SAE High Octane Fuels Symposium.

Hurdles and Resolutions to HOF Adoption

30 hurdles 94 potential resolutions identified, categorized, and discussed

Tracking #	Hurdle	Type	Drivers	Vehicle Mfrs.	Fuel Retailers	Fuel Producers
1	Level 1 hurdles (most formidable hurdles—show-stoppers if not properly addressed)					
1.1	Challenges building supply and demand in concert with one another	Logistical	X	X	X	X
1.2	Investments in ethanol face regulatory risk	Regulatory		X	X	X
1.3	Misfueling legacy vehicles on HOF	Behavioral	X	X	X	
1.4	HOF is not currently a certification fuel, needs to be "readily available and used" first	Regulatory		X		
1.5	Reid Vapor Pressure (RVP) of E25 (with current blendstock) would be too high, and therefore illegal	Regulatory				X
1.6	HOF is not an EPA-registered fuel	Regulatory			X	X
1.7	Future CAFE calculation may not adequately reward HOFVs for improved efficiency	Regulatory		X		
1.8	Cost of upgrading a retail station to offer HOF	Economic			X	
1.9	Problem if HOF price exceeds that of regular gasoline	Economic	X	X	X	X

Vehicle Market Adoption Simulation

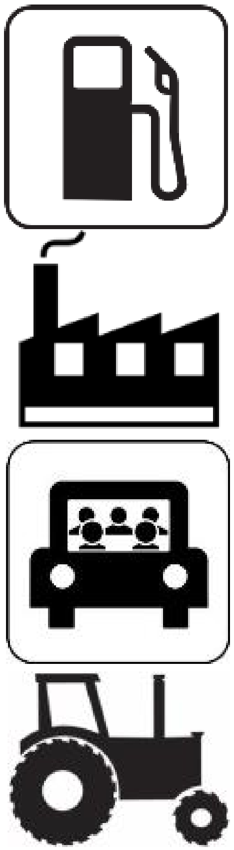


- **All scenarios achieved a substantial percentage (43%–79%) of the light-duty vehicle stock by 2035**
- **More HOFVs are adopted if HOF is E40 (vs. E25) if they offer greater fuel cost savings and GHG benefit**
- **$2,500 purchase incentive boosted 2035 penetration 32% in consumer determined scenarios**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

Fuel Supply Chain Simulation

Results show <u>potential</u> for significant HOF consumption in 2035 under the scenarios modeled

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



Where are the bottlenecks?

- **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:
- **Construction rate of new biorefineries is limiting factor**
  - Unless enough time passes to allow construction to catch up (circa 2025). In which case:
- **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)
- **Feedstock availability and cost are <u>not</u> the limiting factors in any scenarios**

Well-to-Wheels (WTW) Analysis of High Octane Fuels

Michael Wang

Systems Assessment Group

Energy Systems Division

Argonne National Laboratory

Motivation for HOF WTW: Addressing Tradeoff Between Vehicle Efficiency Gain and HOF Production Penalty

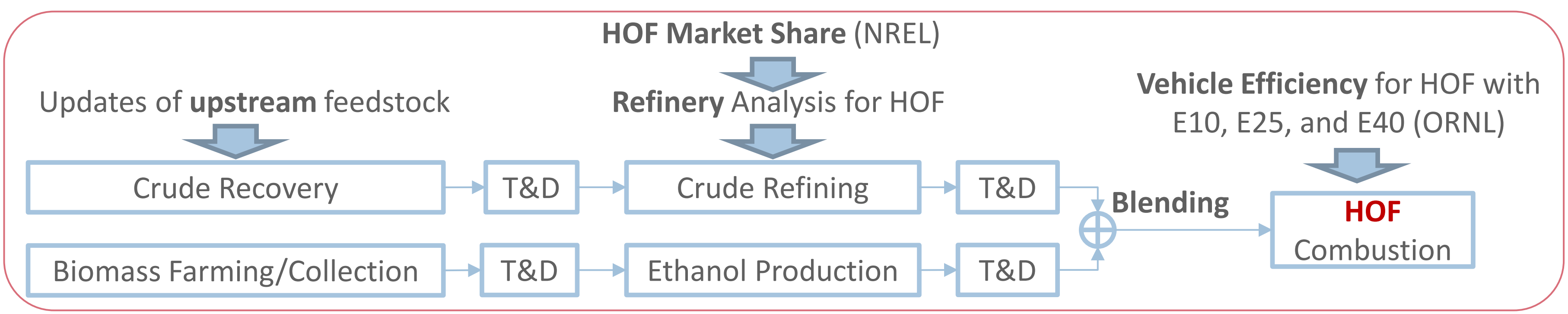
Reference	RON	Efficiency Gain (%)		Comment
		Engine	Vehicle	
Nakata et al. (2007)	100	7.4		Constant load, Compression ratio = 13
Leone et al. (2014)	102		5.5–8.8	Compression ratio = 13
Hirshfeld et al. (2014)			6–9	Compression ratio =13
Speth et al. (2014)	98		3.0–4.5	
This study	100		5	We considered **10%** for E40 as a sensitivity case

Scope of HOF WTW:

- Petroleum refinery linear programming (LP) modeling of producing HOF with different ethanol blending levels
  - ✓ Analyze refinery challenges to meet RON and RVP requirements
- WTW analysis of HOF-fueled vehicles with refinery efficiency and vehicle efficiency

WTW Approach

- Petroleum refinery LP modeling for PADDs 2 and 3 (with Jacobs Consultancy)
  - Key fuel spec constraints: RON and Reid Vapor Pressure (RVP)
  - **HOF market share** is a key parameter for refinery LP modeling (from vehicle choice models by NREL)
  - **No new capital investment assumed for refineries**
  - **Gasoline export** is allowed with discount after the US gasoline demands are met
- Crude recovery and ethanol production
  - Canadian oil sands, and cellulosic and corn ethanol production were updated
- Vehicle efficiency gains
  - Baseline regular gasoline (E10, RON 92) fuel economy: 23.6 mpg
  - Two assumptions for HOF MPGGE relative to regular E10:
    - **Uniform 5% MPGGE gain** based on 100 RON for E10, E25, and E40 (RON is the driver)
    - **Fuel parity** gain assumption: **10% gain** for HOF E40

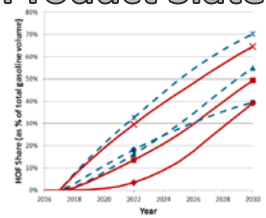


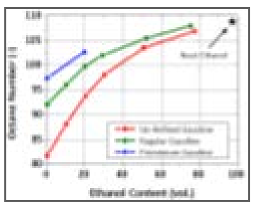
WTW System Boundary

Detailed Refinery LP Modeling Needed for Reliable WTW

Crude Slate

Product Slate

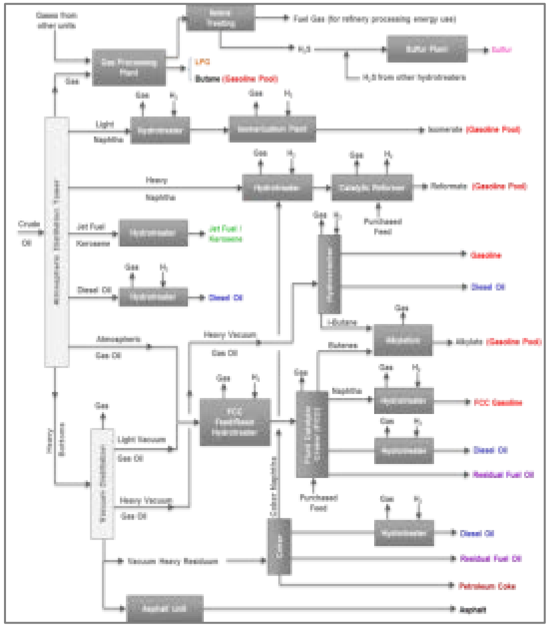




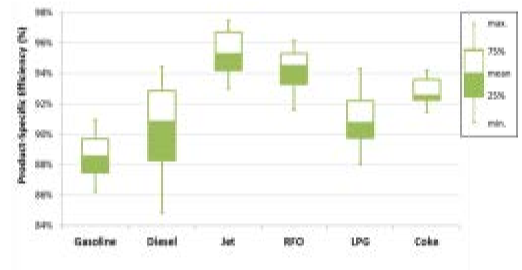
Fuel Specifications (RON, RVP)

Economic factors

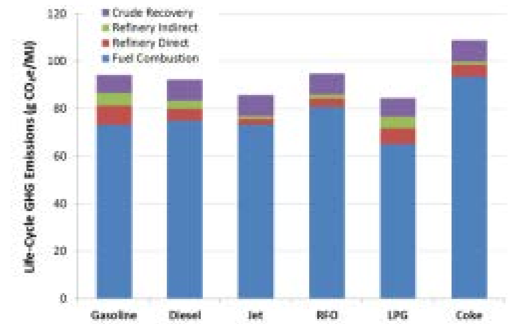
Refinery LP Modeling



Refining Efficiency

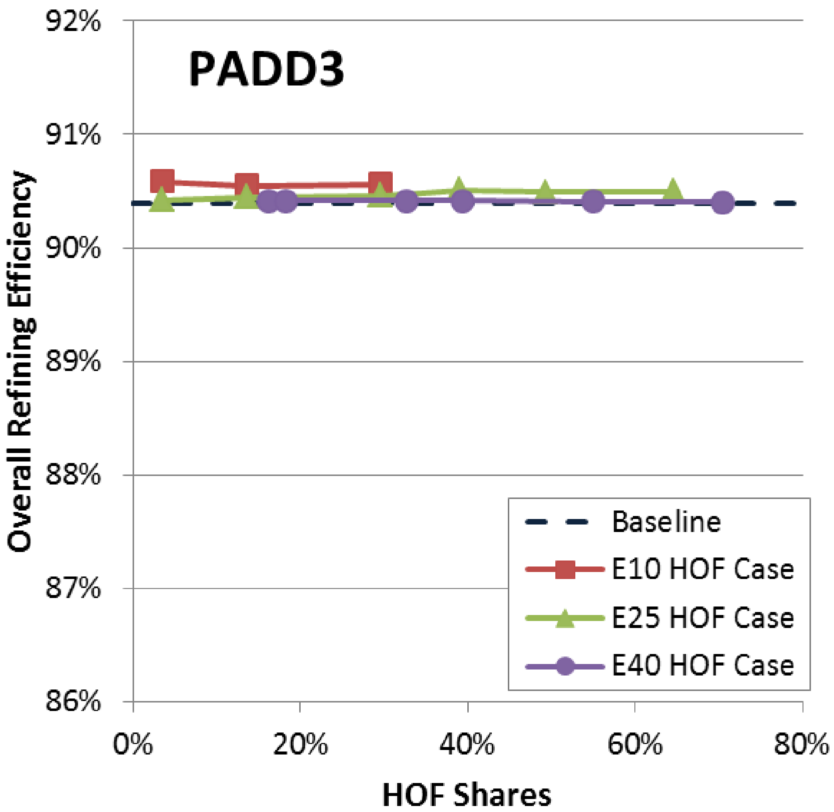


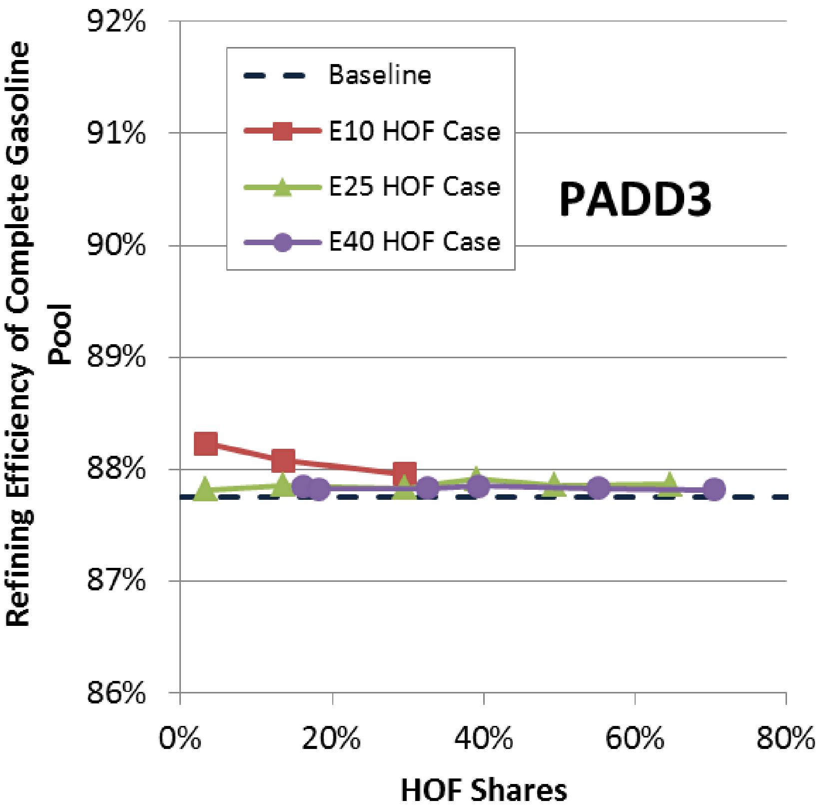
Life-Cycle Analysis



- ❑ Reliable modeling of complex refinery industry
- ❑ Detailed modeling results of refining process units, intermediate products flow rates, utility consumptions, etc.
  - ✓ To evaluate the energy and emissions burden of individual refinery products

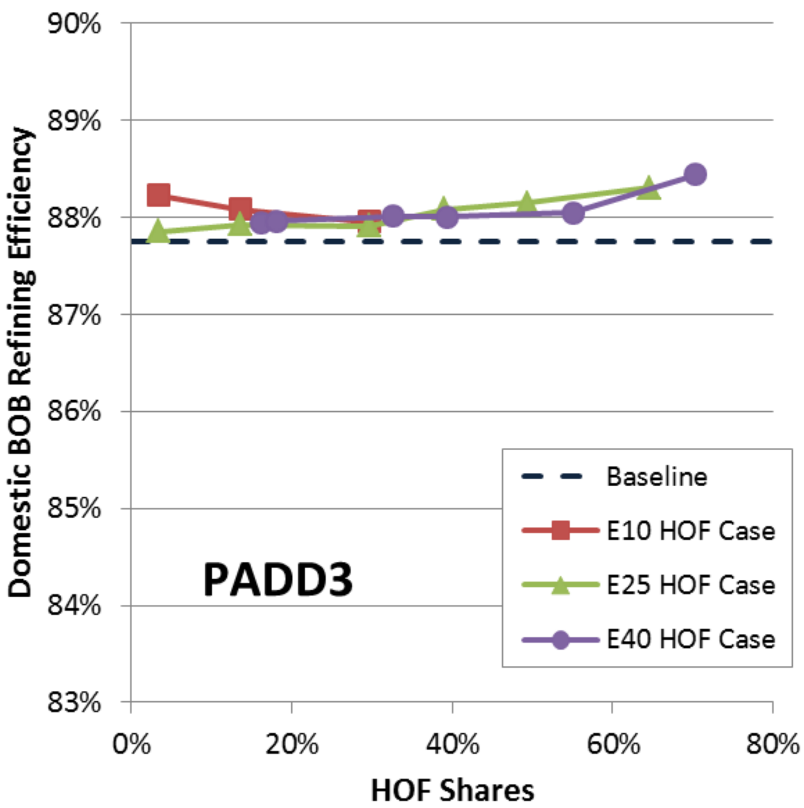
Overall Refinery and Gasoline Blendstock Energy Efficiencies Are Subject to Small Changes with EtOH Blending Level and HOF Share

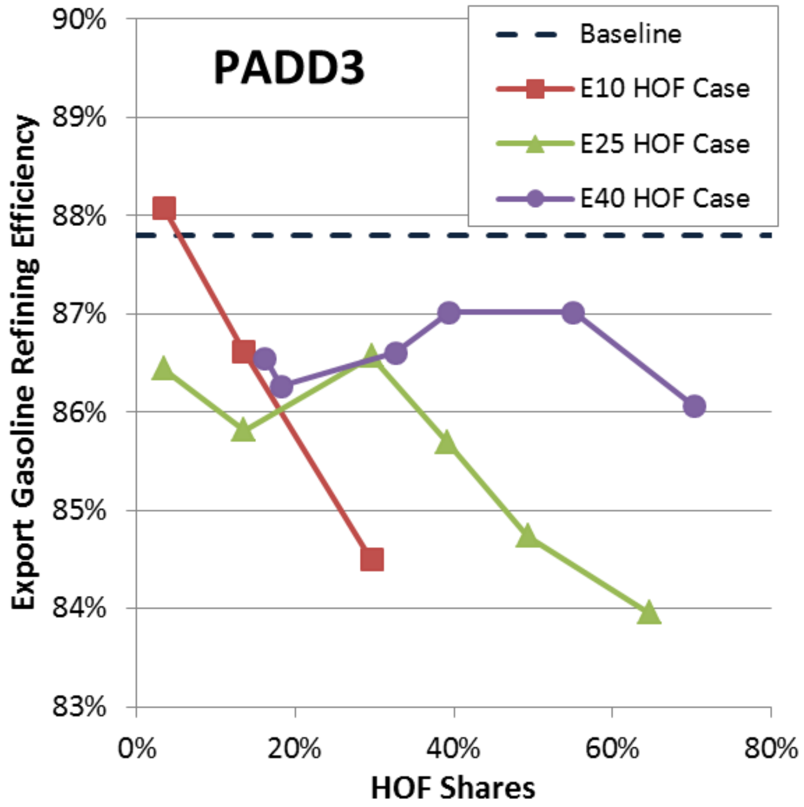




- BOB: Blendstock for Oxygenate Blending; BOB + Ethanol = Finished Gasoline
- E10 HOF is feasible only up to ~25% of gasoline market share
  - A result of **no new capital investment assumption**
- PADD2 shows similar trends, though with overall lower efficiency

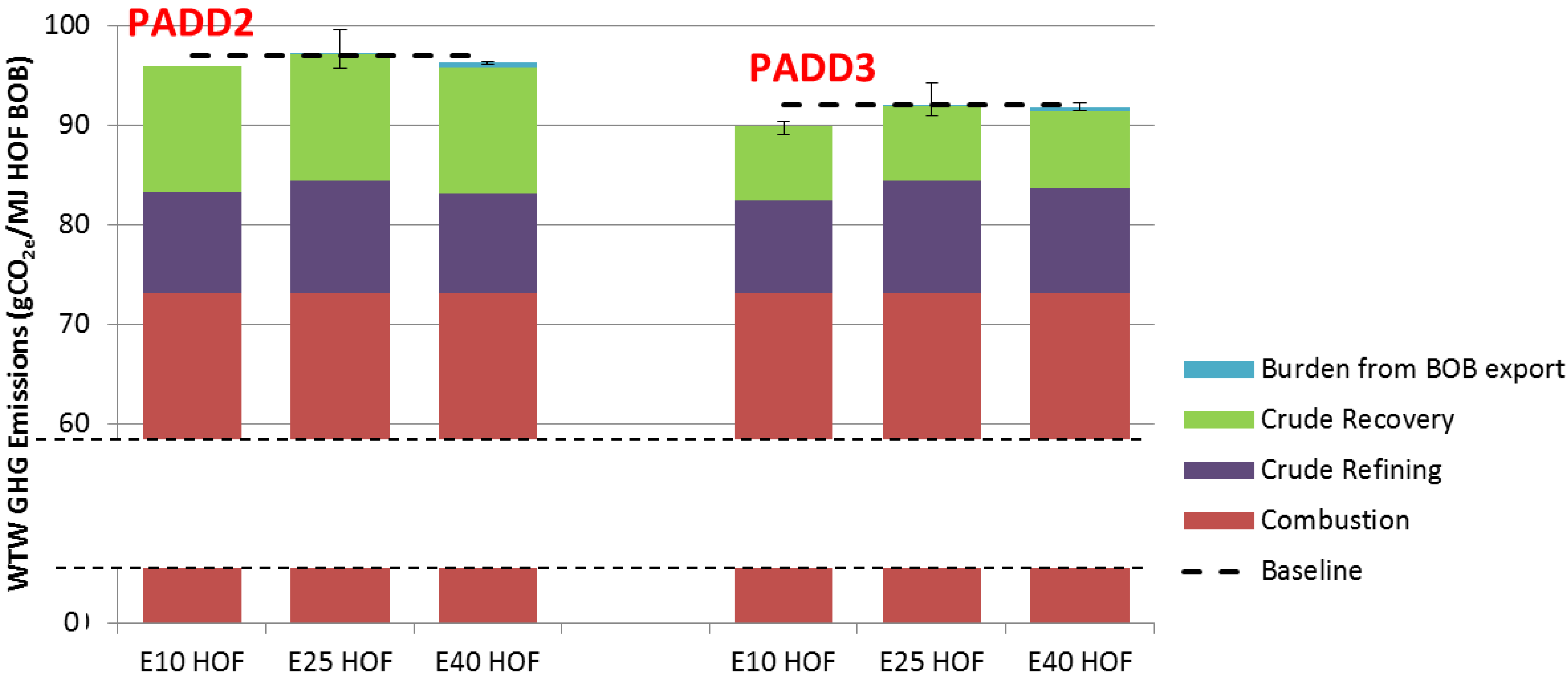
Refining Energy Efficiencies Vary Between Domestic Blendstock and Exported Gasoline





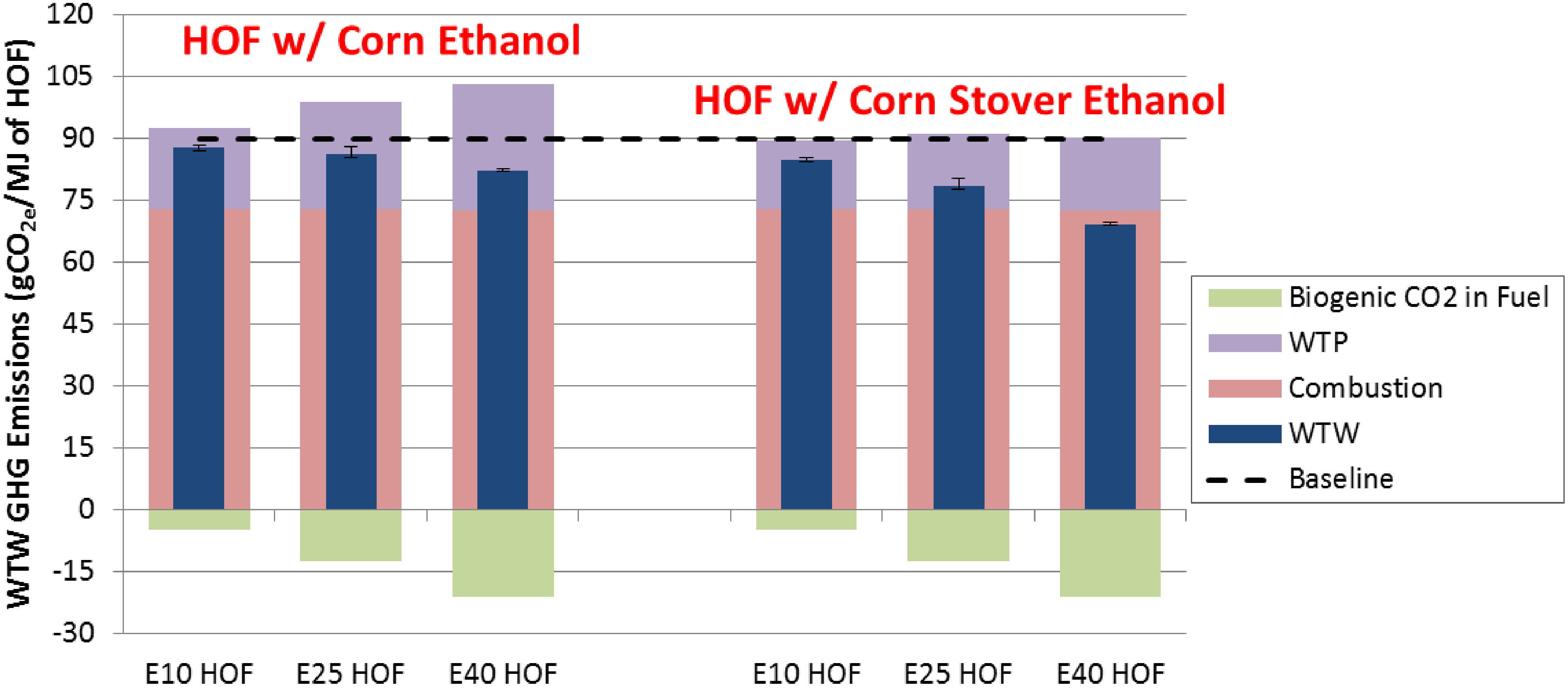
- Domestic BOB efficiency has little change
- Possible spill over of energy penalty from domestic BOB to export gasoline pool
  - Up to 4% drops in export gasoline refining efficiency from the baseline (non-HOF) case
  - Up to 2.5 g CO2e/MJ increases in export gasoline's GHG emissions from the baseline
- But combined change is small with allocated to HOF (<1 gCO_2e/MJ HOF)

HOF Blendstock: GHG Emission Variation of HOF Blendstock Component Is Small



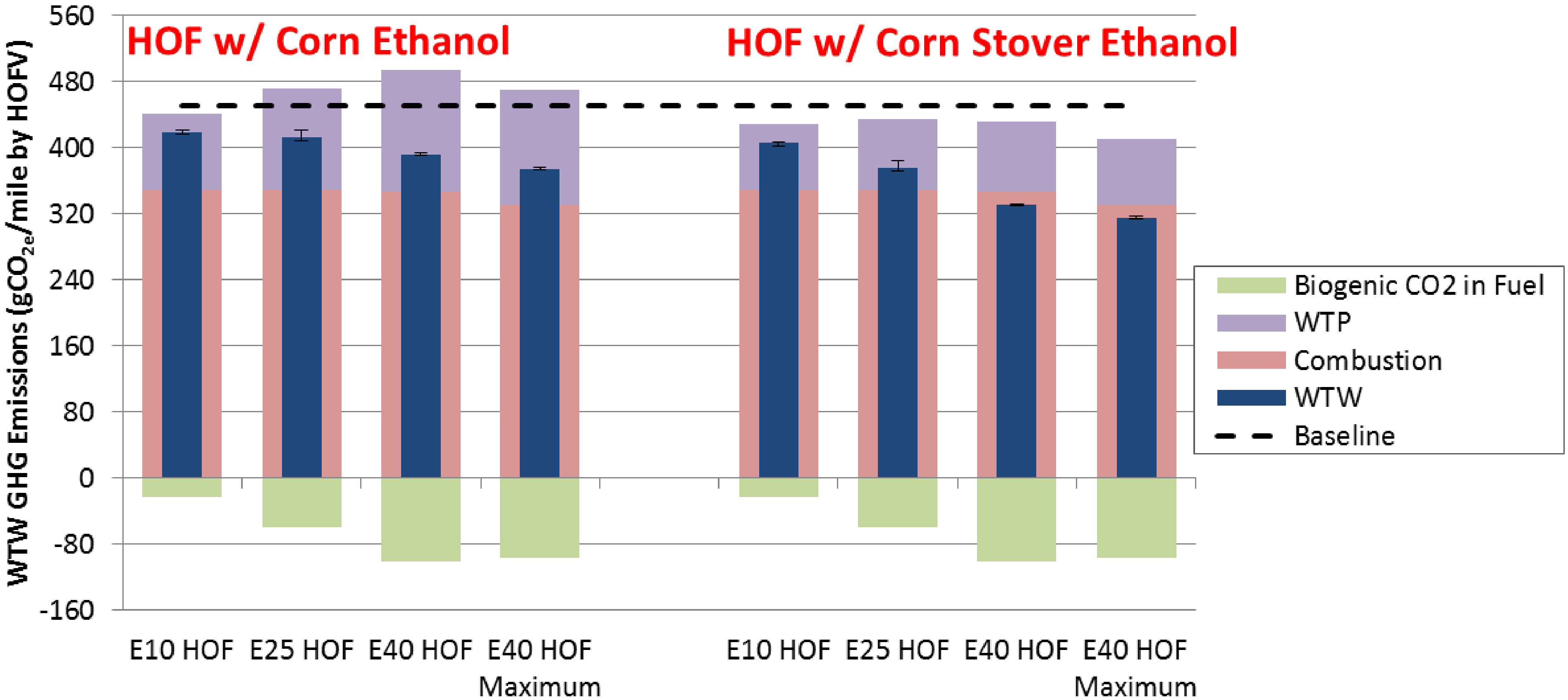
- Larger WTW GHG emissions in PADD2 is due to a larger share of GHG-intensive oil sands
- Adjustment for the spill over is 0.2 gCO_2e/MJ of HOF on average (up to 0.8 gCO_2e)
- Baseline BOB is Business-As-Usual
  - Market shares of different gasoline types: 92% of regular E10 and 8% of premium E10

Finished HOF: Higher Ethanol Blending Level Contributes to Lower WTW GHG Emissions of HOF (per unit of energy results, PADD3)



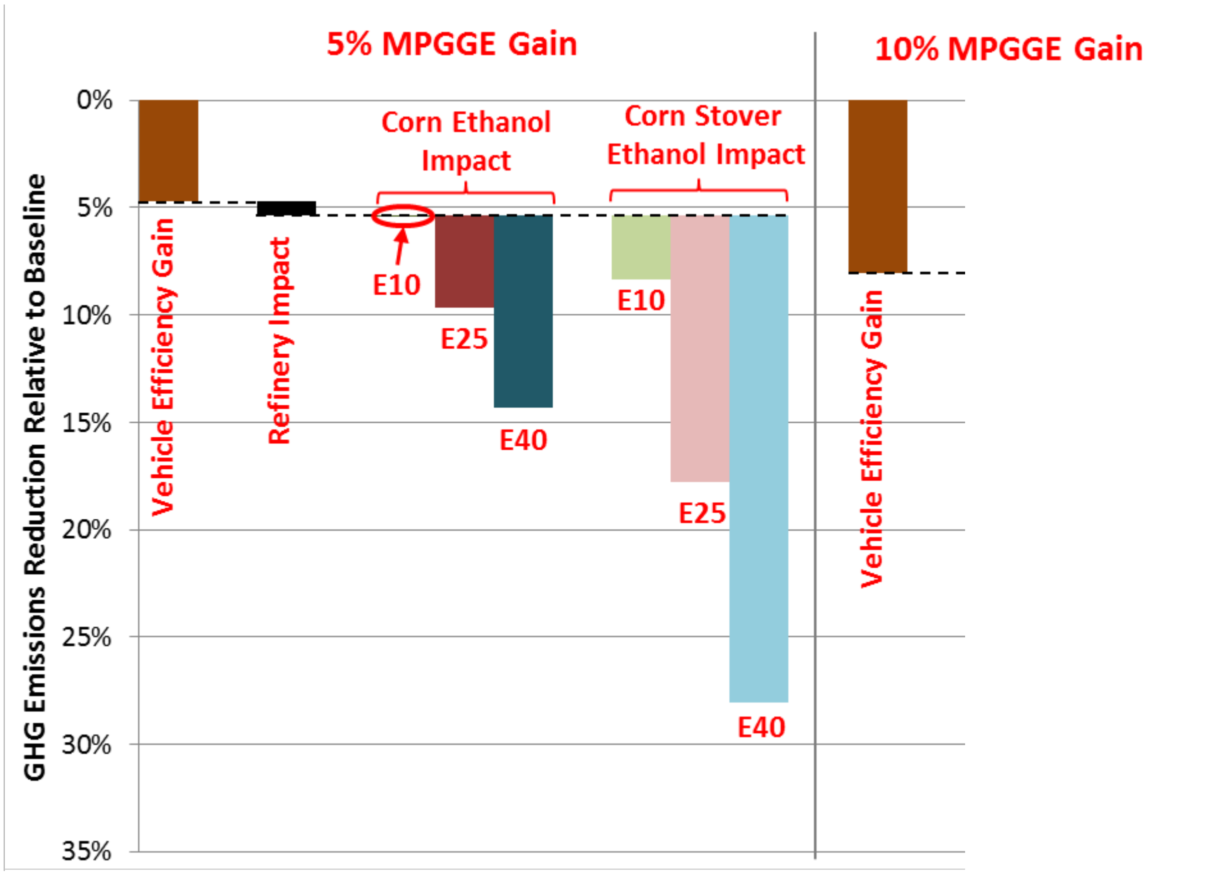
- Corn stover ethanol is used as a surrogate for cellulosic ethanol

Vehicle Fuel Economy Gains Provide Additional WTW GHG Emissions Reductions (per mile results, PADD3)



- E10, E25 and E40 HOF → 5% MPGGE gain (volumetric fuel parity at E25)
- E40 HOF Maximum → 10% MPGGE gain (volumetric fuel parity at E40)

Cellulosic E25 and E40 HOF Can Reduce GHG Emissions by Up to 17% and 31% Relative to Baseline Gasoline, Respectively (based on per mile results)



- GHG reduction w/ vehicle efficiency gain: 5% with 5% MPGGE gain, 9% with 10% MPGGE gain
- Refinery GHG Impact: <1% (small)
- Ethanol Blending GHG Impact
  - Corn Ethanol: 0% for E10, 4% for E25, 9% for E40
  - Corn Stover Ethanol: 3% for E10, 12% for E25, 23% for E40

WTW Conclusions

- Vehicle efficiency gains and ethanol blending are the two dominant factors for WTW GHG emissions reduction
- Impacts of HOF production on refinery GHG emissions is relatively small
- Ethanol can be a major enabler in producing HOF with significant vehicle efficiency gains and a large reduction in WTW GHG emissions

Summary

- Ethanol blended at 25 to 40% provides high octane number and fuel/air charge cooling
  - E25 to E40 can be used in over 17M FFVs currently deployed
- HOF enables production of more efficient, optimized vehicles
- Biofuel production and vehicle adoption models suggest potential HOF consumption of up to 30 billion gallons ethanol in 2035
- WTW GHG emission reductions range from 9-18% for corn ethanol HOF and 17-31% for cellulosic ethanol HOF
- There are challenges to introduction of ethanol HOF
  - Underground storage tanks are likely compatible
  - Fuel dispensing equipment will require upgrading
  - Challenges of developing supply and demand in concert