Benefits of High Octane, Mid-Level Ethanol Fuel Blends

25x’25 Webinar
June 18, 2015
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

- Natural Gas: 34.99%
- Coal: 23.27%
- Petroleum: 21.04%
- Nuclear: 9.57%
- Renewables: 11.13%
- Hydroelectric: 2.84%
- Wind: 1.99%
- Biomass: 5.55%
- Solar/PV: 0.49%
- Geothermal: 0.26%

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

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 greenhouse gas (GHG) & energy analysis

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

Robert L. McCormick

25x’25 Webinar Briefing
June 18, 2015
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
  o RON = 109
  o Relatively low cost source of octane

• What about charge cooling?
  o Ethanol almost 3x higher than gasoline
  o MIT study suggests 1 RON unit increase for every 3°C additional cooling

• Optimum blend likely 20-40% ethanol
  o Non-linear benefit of higher octane vs. linear decrease in energy density
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)

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

Most retail stations are small businesses
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
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
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

**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**

**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.

**Time (s)**

<table>
<thead>
<tr>
<th>Time</th>
<th>E10 Regular</th>
<th>High Octane E30</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 MPH</td>
<td>13.3</td>
<td>12.85</td>
</tr>
<tr>
<td>80 MPH</td>
<td>13.2</td>
<td>12.75</td>
</tr>
</tbody>
</table>

**15 MPH to 80 MPH WOT Acceleration Time (GMC Sierra FFV, 12 run average)**

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

[Image of ORNL's Sierra results with E30 similar to Car and Driver test with E85]

[Image of CAR AND DRIVER test results]

[Image of Effects of High-Octane Ethanol Blends on Four Legacy Flex-Fuel Vehicles, and a Turbocharged GDI Vehicle]

[Image ofOak Ridge National Laboratory]

[Image of impacts of E85 on FFVs]

Work supported by DOE Bioenergy Technologies Office
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

```
<table>
<thead>
<tr>
<th>Fuel</th>
<th>E0</th>
<th>E15</th>
</tr>
</thead>
<tbody>
<tr>
<td>RON</td>
<td>90.7</td>
<td>97.8</td>
</tr>
<tr>
<td>AKI</td>
<td>87.7</td>
<td>92.6</td>
</tr>
<tr>
<td>Btu/gal</td>
<td>113,100</td>
<td>106,700</td>
</tr>
<tr>
<td>Relative Btu/gal</td>
<td>1.00</td>
<td>.943</td>
</tr>
</tbody>
</table>
```

Addition of 15% ethanol boosts octane, improves engine performance & efficiency.
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
Purpose: Assess the feasibility, economics, and logistics of adopting High Octane Fuel (HOF) by drivers, vehicle makers, fuel retailers, and fuel producers

Strategy:
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**
- 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
- 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


## Hurdles and Resolutions to HOF Adoption

30 hurdles 94 potential resolutions identified, categorized, and discussed

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

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

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](image-url)
Detailed Refinery LP Modeling Needed for Reliable WTW

- 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
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 gCO₂e/MJ HOF)
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$_2$e/MJ of HOF on average (up to 0.8 gCO$_2$e)

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