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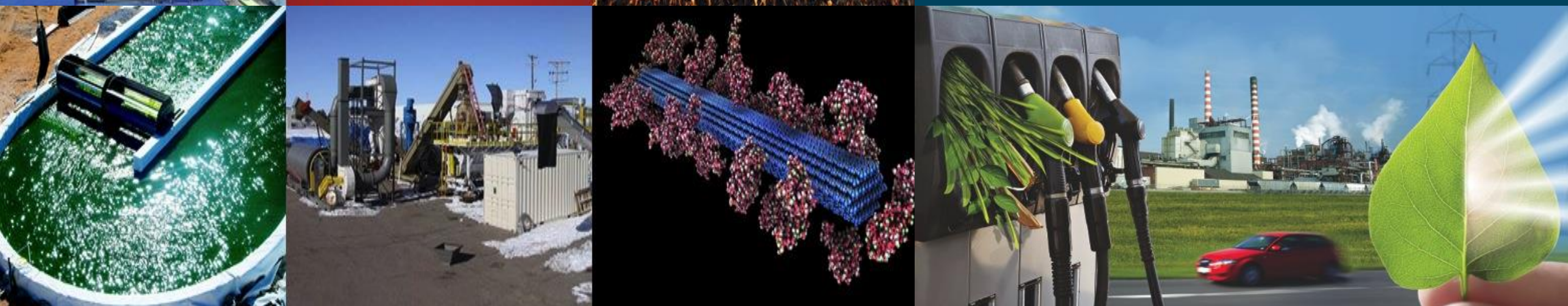


Increasing Biofuel Deployment through Renewable Super Premium

2015 Bioenergy Technologies Office Peer Review

March 23, 2015

Demonstration & Market Transformation Platform

Tim Theiss, ORNL

Bob McCormick, NREL

Jeongwoo Han, ANL

Project Goals are Aligned with DMT & BETO Goals

RENEWABLE FUEL STANDARD

36 billion gallons by 2022

(EISA 2007)

FUEL ECONOMY STANDARDS

2025 CAFE Standards

(U.S. EPA and U.S. NHTSA standards)

EMISSIONS REGULATIONS

↓70% NO_x & PM, 85% NMOG

< 10 ppm sulfur in gasoline

(U.S. EPA Tier 3 regulations)

- BETO Office Goal: *"Enable nation-wide production of biofuels compatible with today's transportation infrastructure, reduce greenhouse gas emissions and displace petroleum-derived fuels …"*
- Renewable Super Premium (RSP) can create additional demand for large amounts of ethanol (move past blend wall) & improved fuel economy in dedicated vehicles (supports biofuels & automobile industries)
- Project is "scoping study" to address barriers, quantify benefits and determine if additional R&D is warranted

Quad Chart Overview

Timeline

- Began: Sept. 2013
- End: Dec. 2015
- Percent complete: 65%

Budget

	FY 13 Funds (for FY14 effort)	FY 14 Funds (for FY15 & FY16 effort)	Total Planned Funding
DOE Funded	$2,500k	~~$2,019k*~~ $1,769k*	~~$4,519K*~~ $4,269k*

*Rounded up to nearest $k from $955

- ORNL – 47% ($2,019k)
- NREL – 36% ($1,550k)
- ANL – 16% ($700k)

Barriers addressed

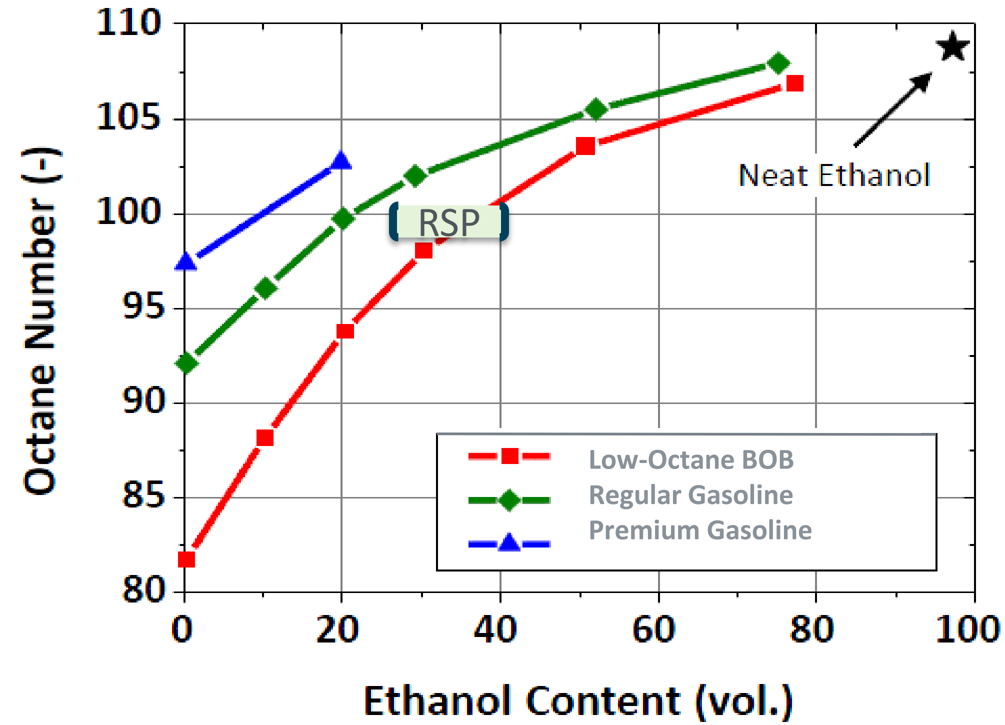
- ✓ It-F: Engine not Optimized for Biofuel
- ✓ Im-H: Availability of Biofuels Distribution Infrastructure
- ✓ It-I: Lack of Awareness and Acceptance of Biofuel as a Viable Alternative
- ✓ At-B: limitations of analytical tools and capabilities for system-level analysis
- ✓ At-A: lack of comparable, transparent, and reproducible analysis
- ➢ Other: The ethanol blend wall!

Partners

- Leveraged with activity from DOE-VTO, EPA-OUST
- Refueling equipment OEMs, regulators, stakeholders
- Vehicle OEMs & stakeholders
- General Motors (~$500k in-kind)
- Direct support
  - Jacobs Consultancy
  - Stanford University
  - University of California, Davis

Motivation for High-Octane, Mid-Level Ethanol Blends

- Higher octane allows for more aggressive engine design, which can improve efficiency
- Non-linear influence of ethanol content → most benefit at lower levels
- Efficiency gains have been demonstrated in research studies at ORNL, Ford & others
- Optimum blend likely 20-40% ethanol → non-linear benefit of higher octane vs. linear decrease in energy density



Reproduced from Stein, SAE2012-01-1277

Define "Renewable Super Premium" as RON ~ 100 with 25-40% ethanol

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Does Renewable Super Premium Warrant Additional Study?

Industry Engagement

Barriers & Opportunities

Information for DOE

Existing Flex-Fuel Vehicles

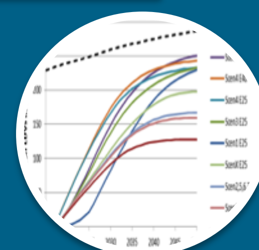
Refinery Impact

Knock Resistance

Existing Infrastructure

Low-Cost Blendstocks

Dedicated RSP Vehicle Efficiency



Market Assessment

GREET

Well to Wheels Environmental performance

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Approach (Management)

- *Use of multi-Lab team*
  - *Multiple disciplines*
  - *Use existing models if possible rather than develop new models (compare & contrast)*
  - *Can not become overly optimistic (have to challenge results/assumptions)*
  - *Analysis assumptions require thorough vetting of results*
- *Strong interactions with stakeholders*
  - *Build upon existing expertise with DOE – VTO & BETO*
  - *Build upon specific strengths, leverage existing work & industrial relationships*
- *Strong communication is key*
  - *Monthly webinars with BETO; regular updates among team; additional interactions among task members; face to face meeting(s)*
  - *Most difficult is communication of pertinent results from different tasks*

The Team …

Jeongwoo Han, Amgad Elgowainy & Michael Wang


Brian West


John Thomas


Paul Leiby


'Debo Oladosu


Rocio Uria-Martinez


Mike Kass

Shean Huff & Jim Szybist – photo not available

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

NREL NATIONAL RENEWABLE ENERGY LABORATORY


Tim Theiss

Bob McCormick


Teresa Alleman


Gina Chupka


Caley Johnson


Aaron Brooker


Emily Newes


Kristi Moriarty


Outline of presentation

Tim - ORNL

- **Project Planning & Communication – ORNL, NREL & ANL**
- **Demonstration of RSP performance in legacy FFVs – ORNL**
- ➢ **Dedicated RSP Vehicle Demonstration - ORNL**

Bob - NREL

- Knock-resistance of ethanol blends - NREL
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- Refinery analysis - ANL
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Tim – ORNL

- Summary & Future Work

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RSP in Legacy Flex-Fuel Vehicles

Background:

- 17M Flex-fuel vehicles have been sold
- FFVs capable of burning E0 (gasoline) to E85 can legally use RSP today
- FFVs use very little E85 (~ 12 gal/year)
- Reduced range; higher costs/mile

Objective: Determine if today's FFVs offer any performance benefit (acceleration) with RSP

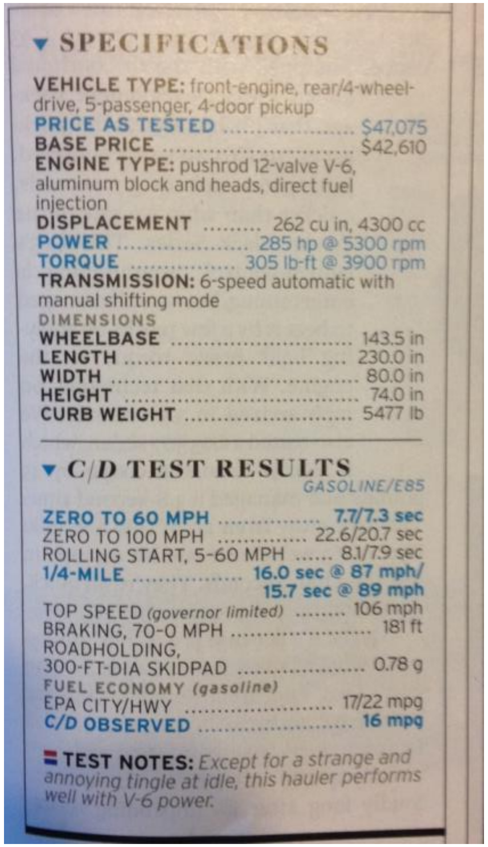
Motivation: Performance improvement in legacy FFVs could enable early adoption of "Renewable Super Premium"

- **Difficult to introduce supply & demand for "alternative fuel" such as RSP (chicken & egg issue)**

✓ **Car & Driver found Silverado FFV had 0.4 sec acceleration benefit with E85**

✓ **People pay for performance**

CAR AND DRIVER



SPECIFICATIONS

VEHICLE TYPE: front-engine, rear/4-wheel-drive, 5-passenger, 4-door pickup

PRICE AS TESTED	$47,075
BASE PRICE	$42,610

ENGINE TYPE: pushrod 12-valve V-6, aluminum block and heads, direct fuel injection

DISPLACEMENT	262 cu in, 4300 cc
POWER	285 hp @ 5300 rpm
TORQUE	305 lb-ft @ 3900 rpm

TRANSMISSION: 6-speed automatic with manual shifting mode

DIMENSIONS

WHEELBASE	143.5 in
LENGTH	230.0 in
WIDTH	80.0 in
HEIGHT	74.0 in
CURB WEIGHT	5477 lb

C/D TEST RESULTS

	GASOLINE/E85
ZERO TO 60 MPH	7.7/7.3 sec
ZERO TO 100 MPH	22.6/20.7 sec
ROLLING START, 5-60 MPH	8.1/7.9 sec
1/4-MILE	16.0 sec @ 87 mph/ 15.7 sec @ 89 mph
TOP SPEED (governor limited)	106 mph
BRAKING, 70-0 MPH	181 ft
ROADHOLDING, 300-FT-DIA SKIDPAD	0.78 g
FUEL ECONOMY (gasoline)	
EPA CITY/HWY	17/22 mpg
C/D OBSERVED	16 mpg

TEST NOTES: *Except for a strange and annoying tingle at idle, this hauler performs well with V-6 power.*

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Performance Improvement of Legacy FFVs With RSP

Approach:

- Evaluate 4 high-sales volume "ethanol tolerant" FFVs
- Prep and test with regular (E10 as baseline) & RSP (E30, 100 RON)

Status:

- Experiments complete (report in progress)
- Fuel economy tracks energy density (~10% less)
- Preliminary results (15-80 mph acceleration)
  - ✓ GMC Sierra (Silverado) – 0.45 sec
  - ▪ Chevy Impala – some benefit
  - ▪ Dodge Caravan – some benefit
  - – Ford F150 – no improvement

Long-term Questions:

- Is it possible to consume more ethanol in FFVs by reducing its concentration?
- Is this an opportunity to introduce RSP for "dedicated RSP" vehicles?

Test vehicle: GMC Sierra V6 FFV

If *half* FFVs on road today (~ 17M) filled up with RSP *half* the time, consume *half-billion* gallons more ethanol!

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High-Octane Efficiency Benefits Demonstrated at the Vehicle Level

- **Acquired vehicle suitable as "dedicated RSP vehicle"**
  - 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 (e.g., Regular, Premium, E10-100 RON, E25-100 RON, E40-100 RON)

GM ATS Vehicle with 2.0 Turbo GDI Engine

Key Assumption: Volumetric Fuel Economy Parity

- **E25 – 5 % efficiency gain**
- **E40 – 10% efficiency gain (stretch)**

- **Implement engine and vehicle based tools to improve efficiency**
- Leveraging on-going engine studies of high-octane fuel for improved efficiency:
  - Competitive FOA project with industry consortium (CRC) to study 10-20 year future technology.
  - WFO and DOE-supported work to study near-future (5-10 year future) engine.

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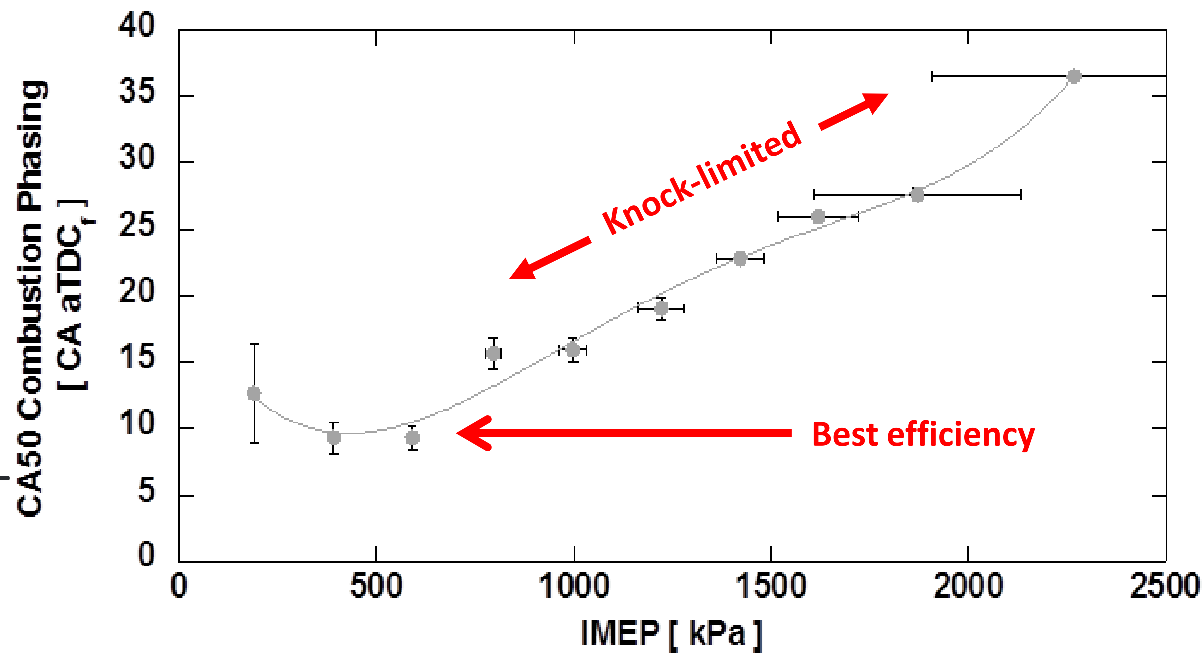
Technical accomplishment / Collaboration

GM-Provided Machined Cylinder Head to Enable Combustion Analysis



- Sloped line represents KLSA – knock limited spark advance
- Information will help us determine best shift schedule for optimum efficiency

Cylinder pressure measurement and crank position measurement allow calculation of the "combustion phasing," which is affected by knock. The higher the load, the later the timing, due to knock, which degrades efficiency. High octane fuels enable more optimum phasing for best efficiency at knock-limited conditions

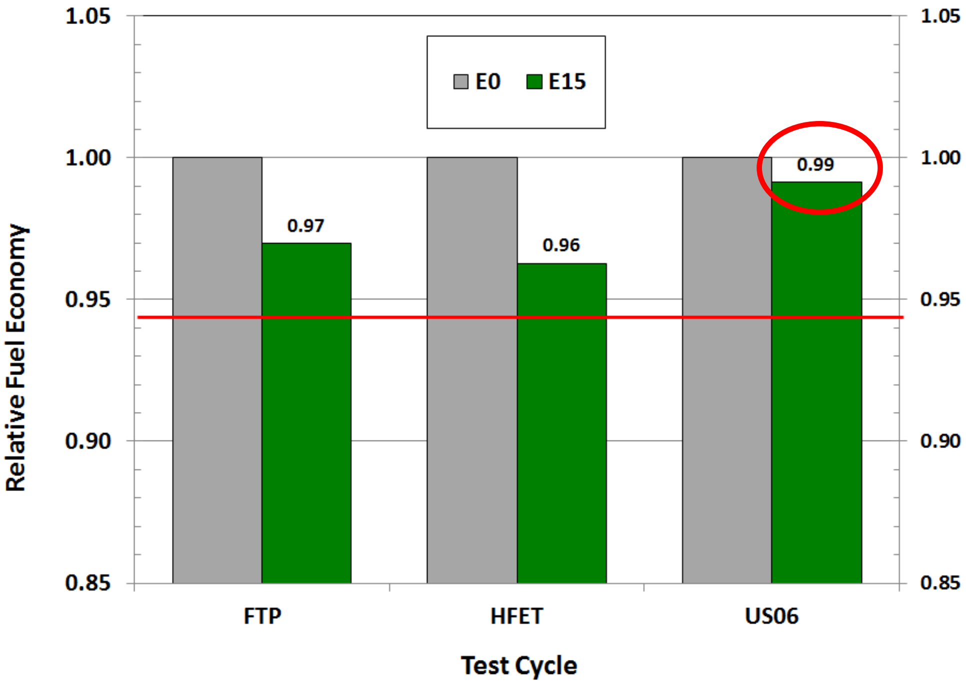
- ***GM Tech support***
  - *High compression pistons*
  - *Engine controls support (spark, boost, etc)*
  - *Ability to monitor cylinder pressure*
  - *Source for taller gears (final drive ratio)*

Instrumented cylinder head installed to support combustion analysis

Benefits of Engine Downsizing with High Octane Ethanol Blend

- **E15-Compatible Ford EcoBoost Fiesta**
  - 1.0 liter, 3-cylinder turbo GDI engine
  - Premium fuel recommended for severe duty cycle (e.g., US06)
  - Smaller engine is more "knock limited"
- **Experiment:**
  - Blend regular E0 with 15% Ethanol (98 RON, E15 Premium RON)
  - FTP (City), HFET (Hwy), and US06 (high-load cycle)
  - *No Changes* to calibration or shift schedule
  - ➢ **Results within 1% of Volumetric Fuel Economy Parity with E15 on US06 test → almost 5% efficiency gain**
  - E15/E0 energy density ratio is comparable to E25/E10 ratio!

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

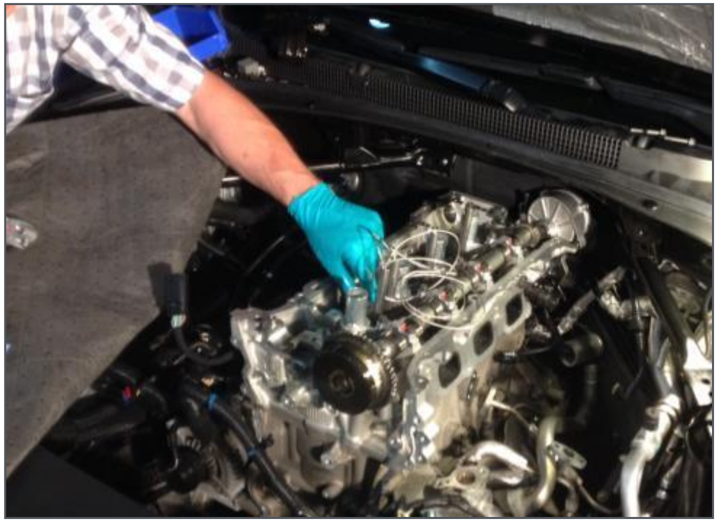


Future Work

- **RSP in Legacy FFVs:**
  - Report results (March milestone)
  - Try RSP in market (beyond scope)
- **Dedicated RSP vehicle:**
- **Demonstrate downspeeding/downsizing**
  - Manual Transmission will readily enable downspeeding
  - Vary shift schedule and/or change final drive
  - Change dyno setup to simulate larger vehicle (test weight, coefficients)
- **Milestone: Demonstrate "dedicated" RSP vehicle efficiency – Sept. 2015**
- **Project can not "optimize" vehicle for RSP**

Results will demonstrate possible vehicle efficiency gains with RSP

Compare high octane from ethanol and petroleum



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Outline of presentation

Tim - ORNL

- Project Planning & Communication – ORNL, NREL & ANL
- Demonstration of RSP performance in legacy FFVs - ORNL
- Dedicated RSP Vehicle Demonstration - ORNL

Bob - NREL

- **Knock-resistance of ethanol blends - NREL**
- **Low-cost blendstocks - NREL**
- **Infrastructure assessment for RSP – NREL & ORNL**
- **Market assessment of RSP – NREL & ORNL**

Jeongwoo - ANL

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

Tim – ORNL

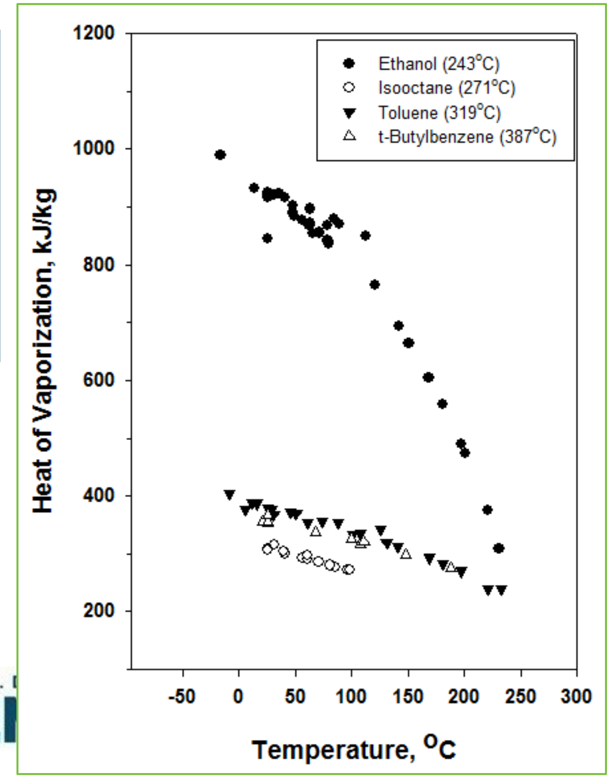
- Summary & Future Work

Knock Resistance Properties

- Aggressive engine design for fuel economy increases T and P in engine
- Fuel must be more resistant to autoignition (knock)
  - Higher octane number (high octane fuels – HOF)
  - Fuel evaporation also cools fuel/air mixture
- Heat of vaporization (HOV) of gasoline ethanol blends not quantified
- Important fuel parameter for engine design/fuel specification

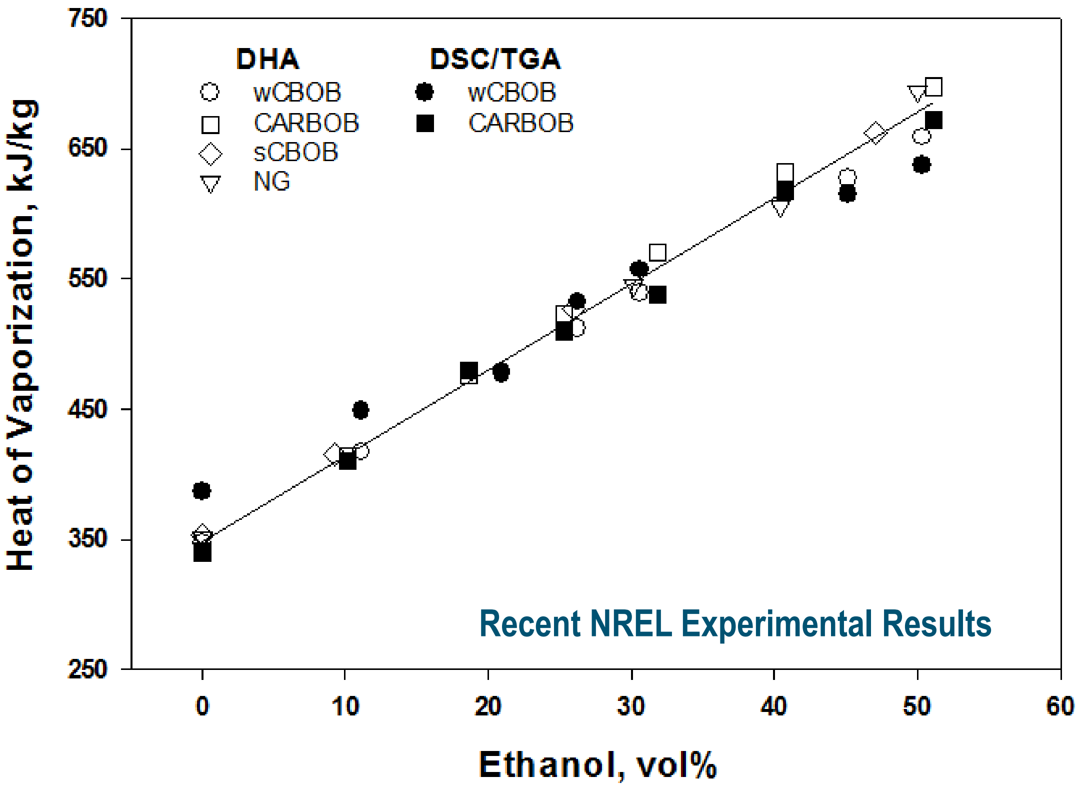
<u>Objective:</u> Develop a description of fuel knock resistance for ethanol blends that incorporates both octane number and evaporative cooling effects

<u>Approach:</u>
- Develop methods for measuring HOV of ethanol-gasoline blends
- Knock-limited spark advance experiments in single-cylinder engine
- Proposals for knock resistance metric



Knock Resistance Properties

- HOV measured by DSC/TGA and detailed chemical analysis and calculation
- Good agreement between methods
- **Very little variation in hydrocarbon blendstock HOV**
- **HOV function of temperature and ethanol content**



Implications for engine industry:

- Variation in HOV is much less than variation in octane number
- Much less complex situation than many envisioned
- Exx blend HOV may be accurately estimated from ethanol content

FY14 Milestone Report (summarized in peer reviewed technical paper to be published in April 2015)

Low Cost Blendstocks

- **Because of high octane number of ethanol, a conventional gasoline blendstock may not be necessary**
  - Lower cost material could be used
- **Natural gasoline, a byproduct of natural gas production:**
  - Dramatic recent increase in production – predicted 600,000 bpd in 2018
  - Cost significantly less than conventional gasoline ($1.22/gal on March 4)
  - High vapor pressure – advantage for blending with high levels of ethanol

Objective: Determine if binary blend of low cost blendstock (natural gasoline) and ethanol can produce compliant mid (RSP/HOF) and high-level ethanol blends (Flex-Fuel) to reduce consumer cost

Approach:

- Determine range of natural gasoline quality and fully characterize properties (8 samples)
- Produce Flex Fuel blends and determine final blend properties
- Validate commonly used vapor pressure models for these blendstocks (for complying with vapor pressure requirements)

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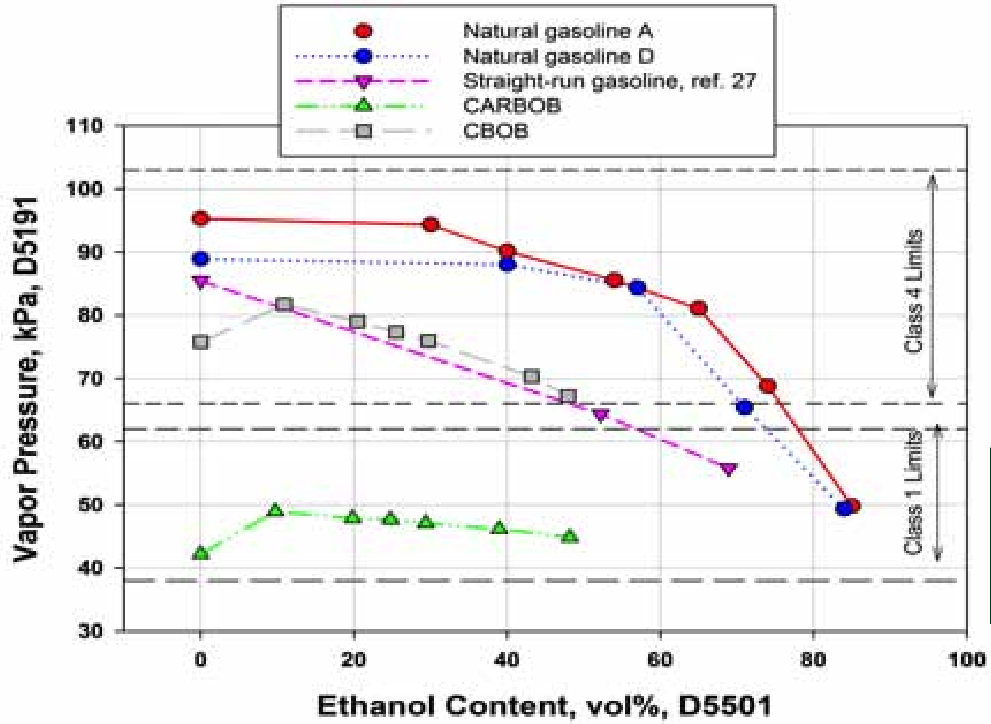
Low Cost Blendstocks

- Natural gasoline quality was highly similar in all 8 samples
  - Sulfur content varied from 4-145 ppm
  - Octane approximately 70
- Blends met D5798 requirements for vapor pressure, for both summer and winter
- Thermodynamic model provides predictions within analytical variability of measurements – easily used by blenders



Class/RVP Range	Natural Gasoline A	Natural Gasoline D
Class 1: 38 – 62 kPa	E78 - E83	E74 - E83
Class 2: 48 – 65 kPa	E76 - E83	E71 - E83
Class 3: 48 – 65 kPa	E61 - E80	E58 - E77
Class 4: 66 – 103 kPa	E51 -E76	E51 - E71

FY14 Milestone Report (summarized in peer reviewed technical paper to be submitted March 2015)

Low Cost Blendstocks

- DOE funded research with natural gasoline ended in FY14
- USEPA is interested in expanding use of E51-85 (Flex-Fuel) in order to meet RFS targets
- At the start of FY15 EPA executed $100,000 interagency agreement with NREL to continue and expand the FY14 DOE funded work on natural gasoline-ethanol blends
  - Includes three component blends: ethanol-natural gasoline-conventional BOB

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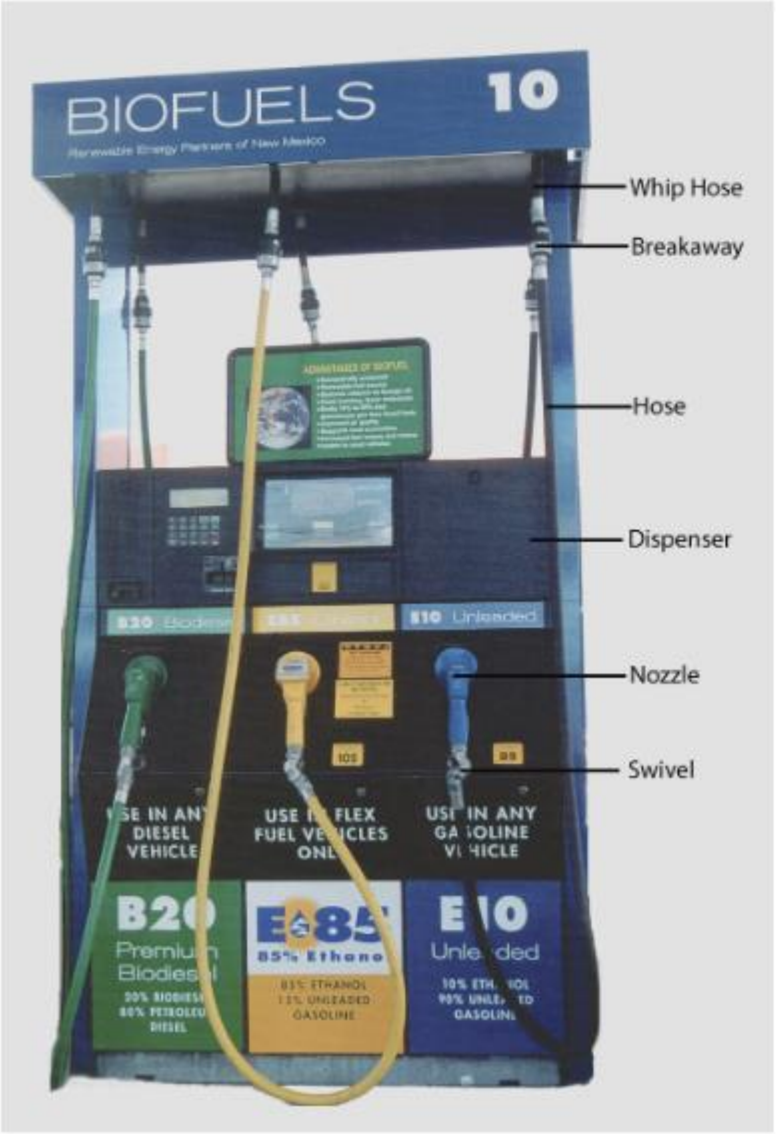
Infrastructure Assessment

Objective:

Determine the opportunities, barriers, and costs for deploying E25 and E25+ at existing refueling stations

Approach:

- Interviewed and received data from industry groups, regulators, and refueling equipment manufacturers
- Reviewed relevant regulations and standards for refueling stations
- Obtain pricing for E25/E25+ equipment in all categories
- Reviewed past work for synergies



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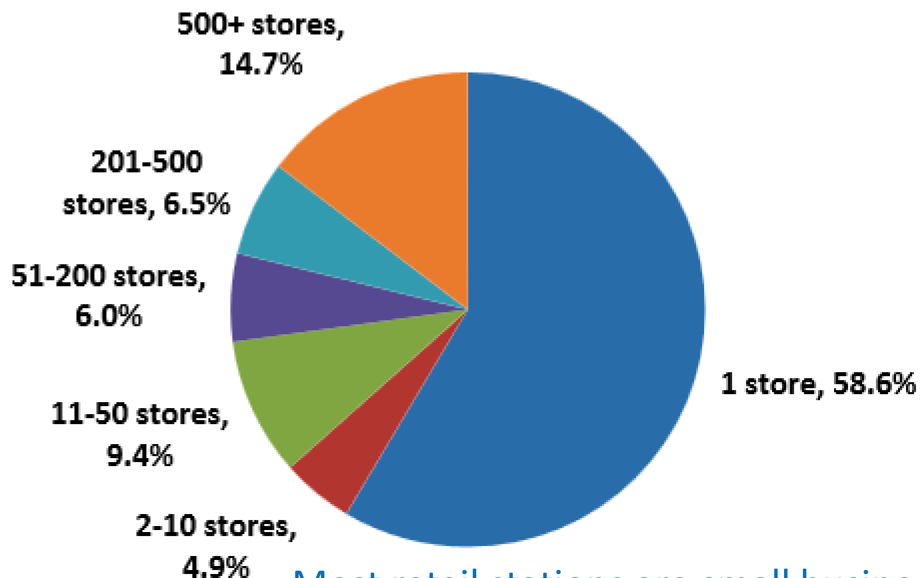
Infrastructure Assessment

- Determined costs to upgrade stations for E25 and E25+
- Identified compatible equipment by manufacturer and model
- Technically E25/E25+ is possible. Marketwise, E25 is less costly and more acceptable to retailers
- Identified issue: refueling stations are not required to keep equipment records - is a challenge for determining compatibility
- Most materials used are compatible



Most retail stations are small businesses

- Estimate that ~ 20% of stations have to carry new fuel for it is be "widely available"
- Infrastructure barrier has been overstated!

Published FY14 milestone report: http://www.nrel.gov/docs/fy15osti/61684.pdf

Market Assessment

Objective: Assess the feasibility, economics, and logistics of adopting RSP by drivers, vehicle makers, fuel retailers, and fuel producers

Approach:

- Identify benefits of RSP to key participants
- Define hurdles to RSP adoption
- Propose resolutions to hurdles

Based on literature review and discussion with industry representatives/stakeholders

- Model vehicle adoption rates for various scenarios (consumer preference model)

Scenarios are resolutions grouped by compatibility and synergies

- Model biofuel production supply chain

Industry and Stakeholder Interactions

Drivers	*Vehicle Makers*	*Fuel Retailers*	*Fuel Producers*
AAA	General Motors	National Association of Convenience Stores	Renewable Fuels Association
National Association of Fleet Administrators	Honda		Poet
National Automobile Dealers Association	Ford		ICM Inc. and Ethanol Across America
	Mercedes		Magellan Midstream Partners
	USCAR Fuels WG		BP

Examined Eight Market Adoption Scenarios

- Mandated deployment of RSP/RSPV (all vehicles starting in MY18 and largest 20% of stations)
  - *Rapid deployment bookend - mandate fuel, retail dispensing, and vehicles*
- Replace mid-grade with RSP and convert premium fuel vehicles to RSP-vehicles (RSPV), then highest performance next – saves stations money
  - *Manufacturers proactively convert car models to RSP*
- Price-driven adoption of RSPV (switch most efficient vehicles first) and station subsidies (40% & 80% of incremental cost to upgrade to RSP)
  - *Manufacturers proactively convert car models to RSP*
- Eliminate high altitude gas and introduce ethanol-tolerant, premium-optimized vehicles, mandate all new refueling equipment
  - *Consumer choice/CAFE drivers - but mandate to optimize new vehicles to 98 RON and ethanol-tolerant*
- E85 becomes 51% ethanol (currently a legal fuel), utilize FFV infrastructure; E51 is back-up fuel for RSPV until RSP is available
- Require all new dispensers to be blender pumps (capable of RSP), vehicles are market-driven adoption
- Deploy RSP Regionally (Midwest, CA), build up from existing FFV infrastructure
  - *Consumer choice/CAFE drivers* (applies to the three scenarios above)
- Expensive - new UST and dispensers, $455 incremental cost for vehicles; 20% largest stations must sell RSP by 2023
  - *Slow deployment bookend - E40, new UST and dispenser, high vehicle cost*

Less Aggressive Policy

Examined Eight Market Adoption Scenarios

- Mandated deployment of RSP/RSPV (all vehicles starting in MY18 and largest 20% of stations)
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Considered multiple policies to investigate impact of the assumptions – not predict "correct" scenario

Less Aggressive Policies

Rapid deployment bookend - mandate fuel, retail dispensing, and vehicles

Manufacturers proactively convert car models to RSP

Manufacturers proactively convert car models to RSP

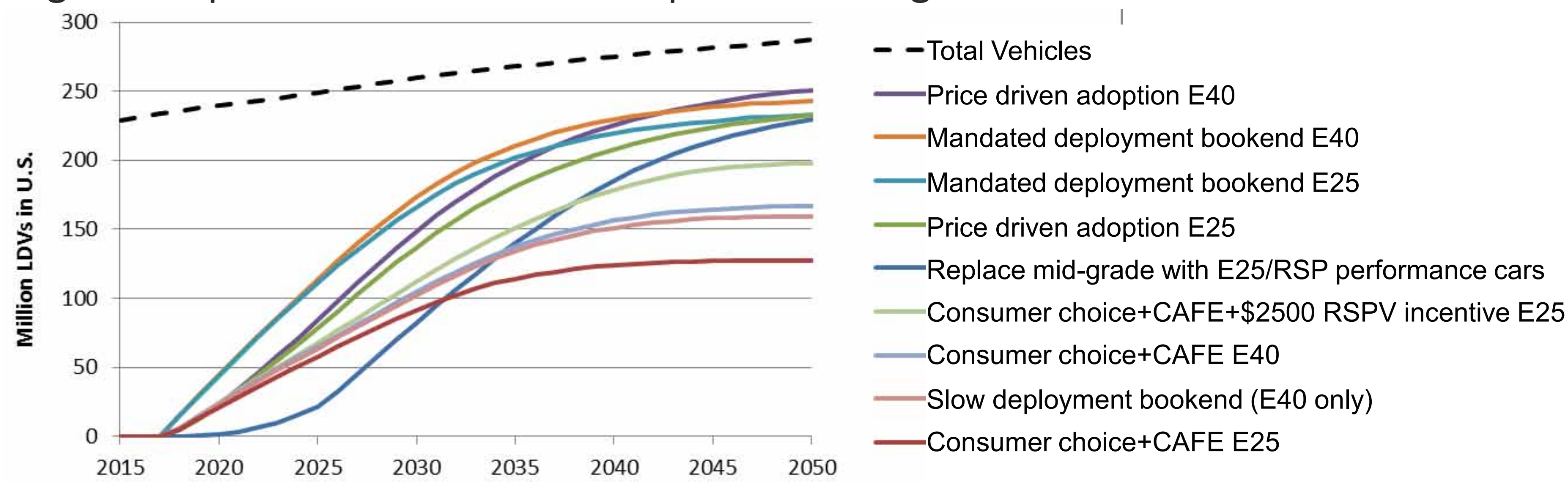
Consumer choice/CAFE drivers - but mandate to optimize new vehicles to 98 RON and ethanol-tolerant

Consumer choice/CAFE drivers

Slow deployment bookend - E40, new UST and dispenser, high vehicle cost

Vehicle Market Penetration Simulation Results

- All scenarios achieved a substantial percentage (44%−87%) of the light-duty vehicle stock by 2050
- More RSPVs are adopted if RSP is E40 because they offer greater fuel cost savings and more CAFE benefit than if RSP was E25.
- $2,500 purchase incentive boosted 2050 penetration 55% in consumer choice driven scenarios
- “Performance vehicles first” conversion was the slowest to gain momentum
- High oil prices had little effect on the rate of RSPV adoption because high gasoline prices enabled CAFÉ compliance through more efficient vehicles



Ethanol Demand from Supply Chain Simulation- Preliminary

- Feedstock availability and cost do not limit deployment of RSP
- In most scenarios, vehicle market penetration sets a ceiling for total potential ethanol usage
- Actual ethanol usage is limited by biorefinery construction rate for:
  - Rapid deployment scenario, E40 case throughout the simulation
  - Scenarios where only RSP refueling equipment is available drive a rapid increase in demand such that biorefinery construction is limiting in initial years (2020-2023)
- In scenarios with significant cost for RSP refueling equipment, RSP availability at retail limits actual demand
- Preliminary results show potential ethanol consumption in 2035 ranging from 28 to 58 billion gal/yr for the E40 rapid deployment scenario and 18 to 32 billion gal/yr for the E25 price driven scenario
- Range is based on different assumptions for vehicle fleet mix and vehicle fuel economy
- Both vehicle market penetration and ethanol demand sensitive to how RSP is treated for CAFE

Future Work

Knock Resistance Properties

- Industry outreach to discuss implications and next steps
  - Presentation at SAE International Congress
- Input on improving HOV measurements and engine knock resistance experimental design

Low-Cost Blendstocks

- Ethanol blending with renewable naphthas
  - Naptha byproduct of commercial renewable diesel production
  - Potentially other samples from technology developers

Infrastructure Assessment

- Determine the ability of terminals and blenders to supply E25/E25+
  - Analyze terminal/blender data and survey terminal/blenders to understand potential barriers

Market Assessment

- Integrating vehicle adoption and fuel supply simulations to study interactions
- Improving and harmonizing assumptions on vehicle market penetration and CAFE treatment of RSP
- Final deliverable is estimated ethanol consumption based on various assumptions and analysis of factors affecting market penetration and demand

Outline of presentation

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- **Refinery analysis - ANL**
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Tim – ORNL

- Summary & Future Work

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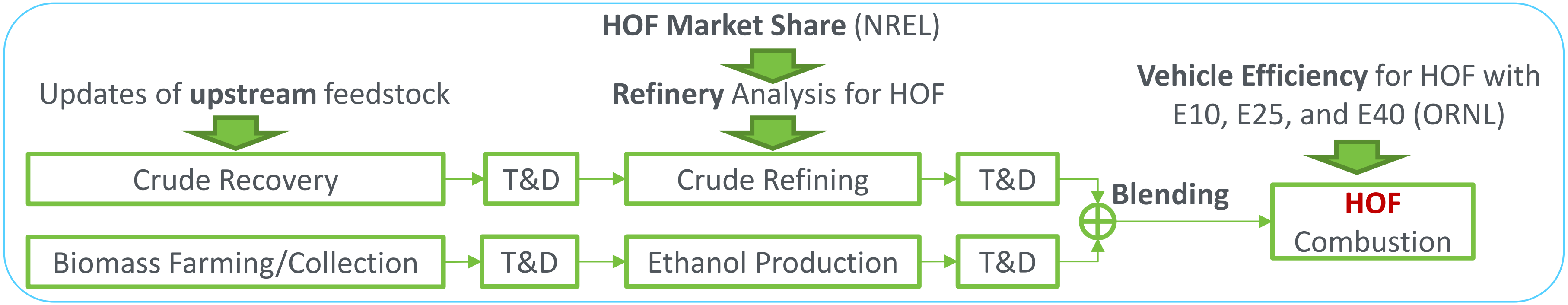
Goal & Overview Statements

- **New definition: High Octane Fuel (HOF) = RON 100 (RSP or E10)**
- Estimate WTW energy and GHG emissions benefits of RSP/HOF with different ethanol blending levels
  - Conduct petroleum refinery LP modeling of producing HOF with different ethanol blending levels
  - Update upstream crude production and cellulosic and corn ethanol production
  - Conduct WTW analysis of HOF-fueled vehicles with a configured GREET
- Estimate WTW GHG emissions benefits of HOF
  - Assess vehicle efficiency gains by high octane fuel
  - Analyze refinery challenges for meet RON and RVP requirements with different ethanol blending levels
  - Estimate GHG benefits of corn and cellulosic ethanol blending for HOF production

WTW Technical Approach

- Petroleum refinery LP modeling for PADDs 2 and 3
  - Key fuel spec constraints: Research Octane Number (RON) and Reid Vapor Pressure (RVP)
  - **HOF market share** is a key parameter for refinery LP modeling (from vehicle choice models)
  - **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

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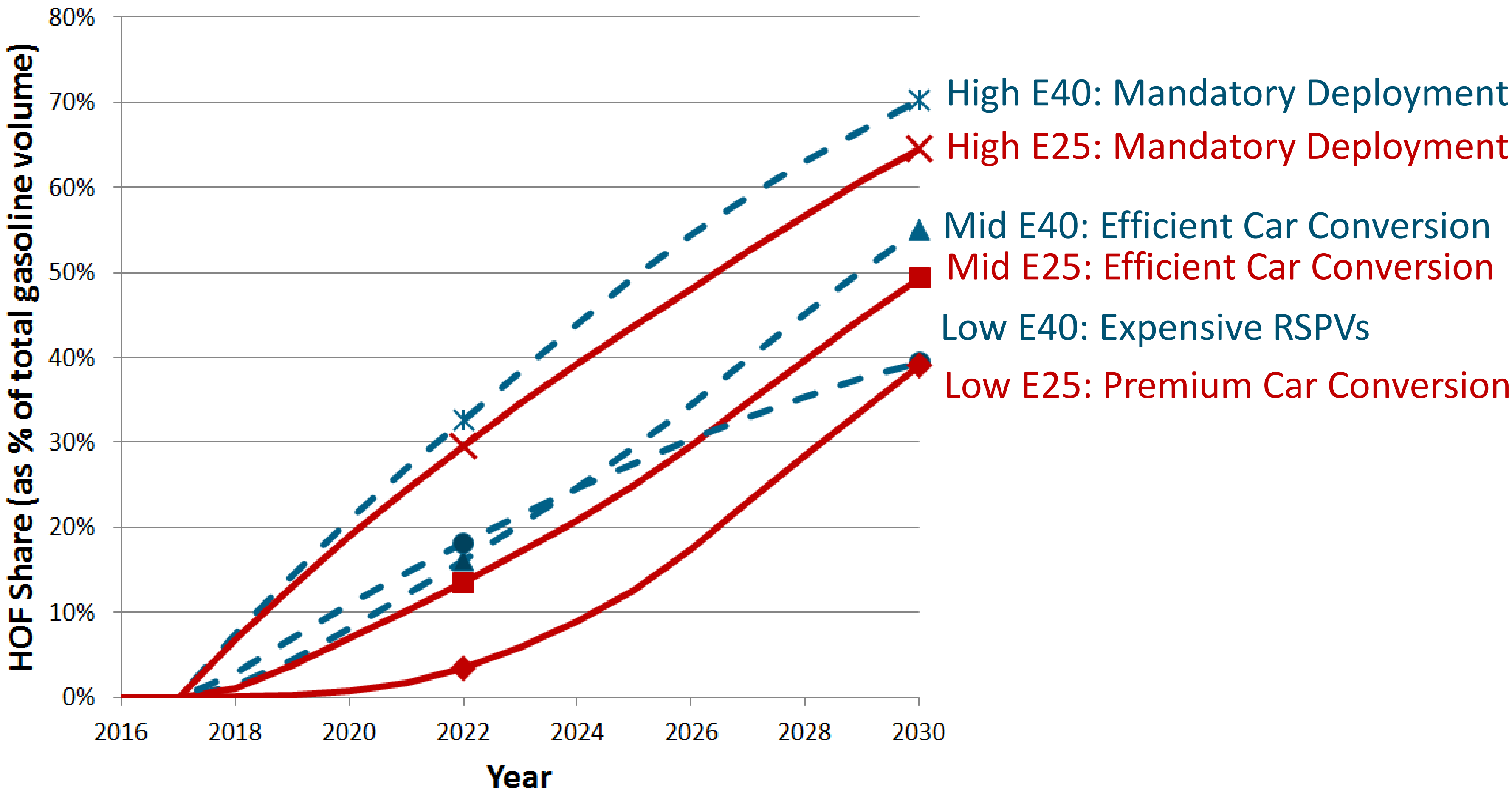
WTW Technical Approach: HOF Market Shares over Time (from NREL)



- Years **2022** and **2030** are selected for refinery LP modeling
  - Covers the entire range of HOF market shares

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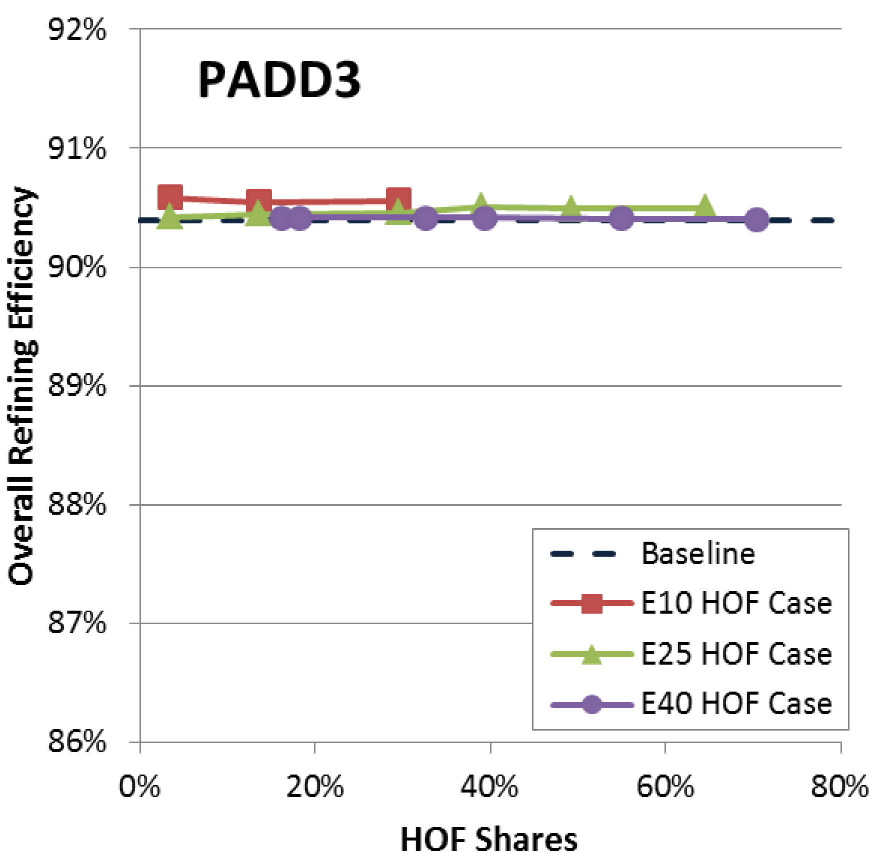
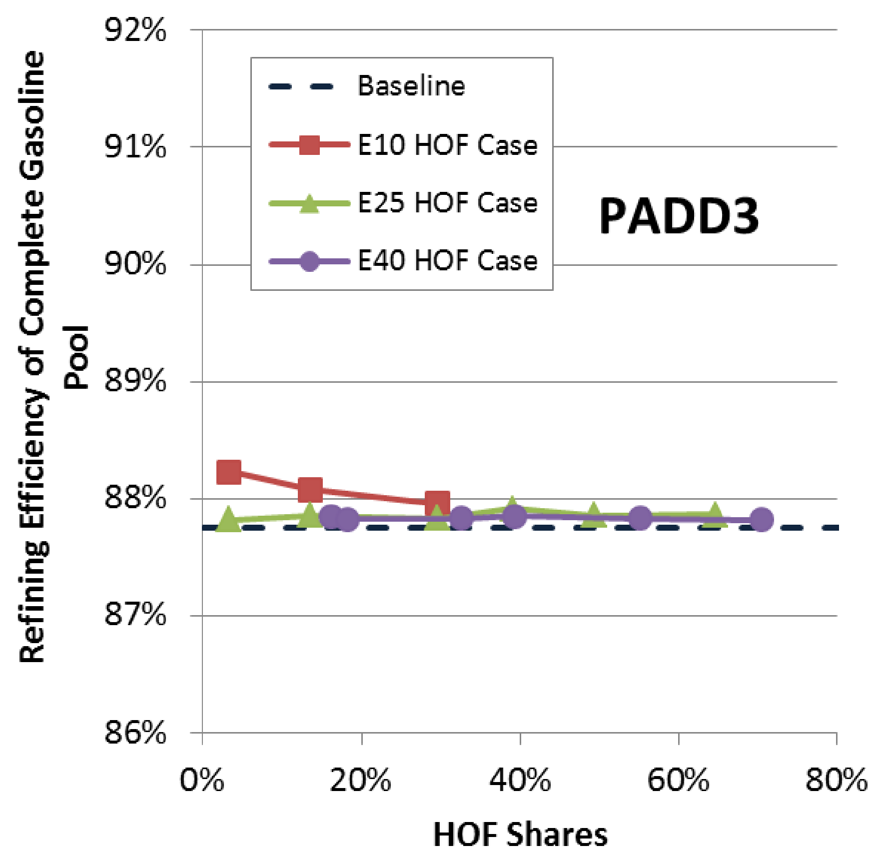
Accomplishment: Overall refinery and gasoline BOB efficiencies are changed little with ethanol blending level and HOF share





- 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

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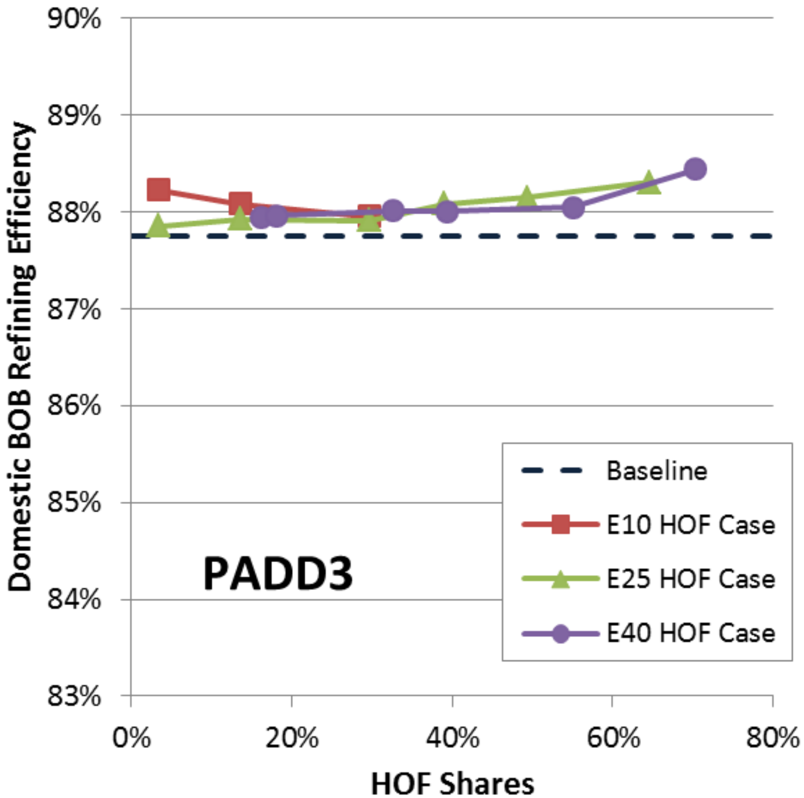
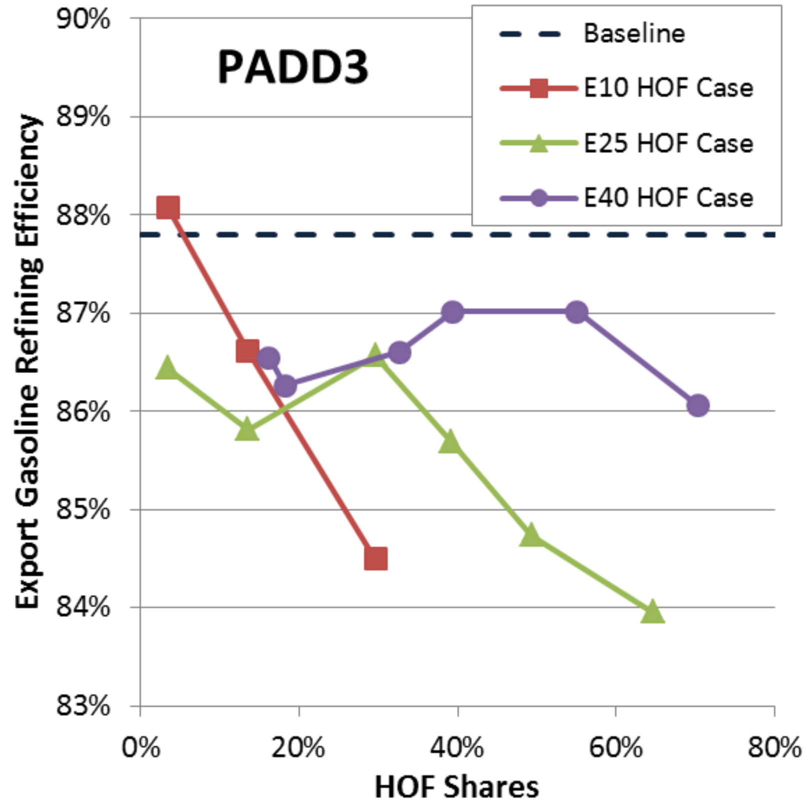
Accomplishment: Refining efficiencies of domestic and export BOB vary





- But the aggregate BOB efficiency is unchanged
  - 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 impact on HOF is small (<1 gCO_2e/MJ HOF)

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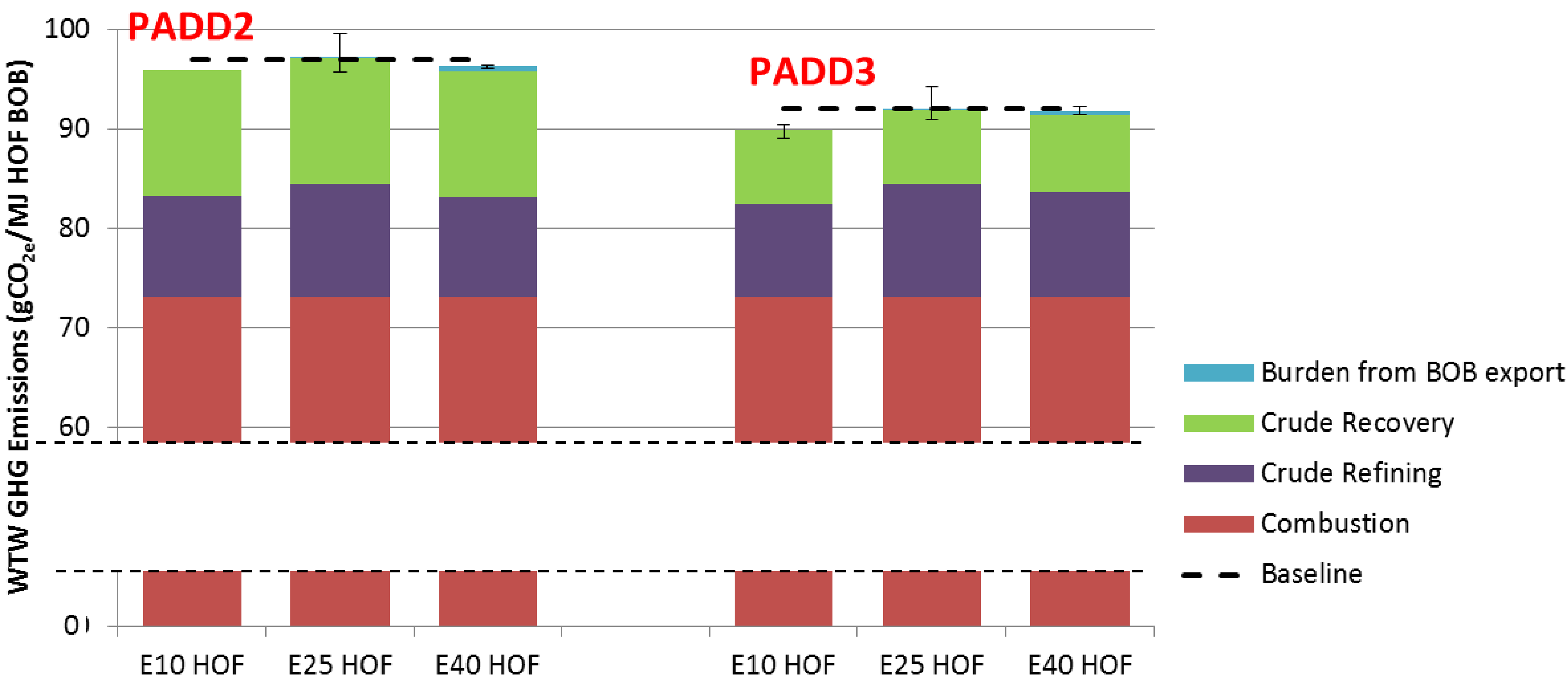
GREET WTW Modeling Results

HOF BOB: GHG emission variation of HOF BOB 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

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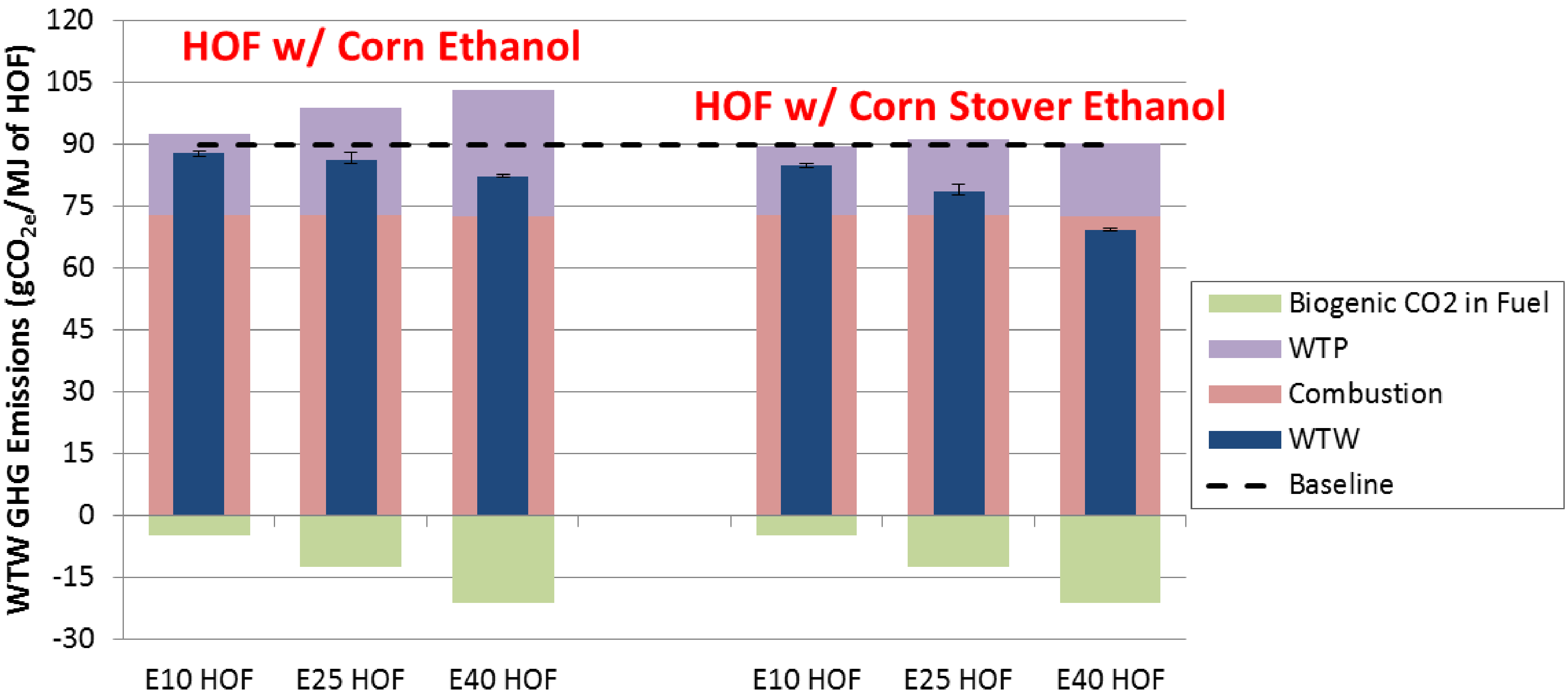
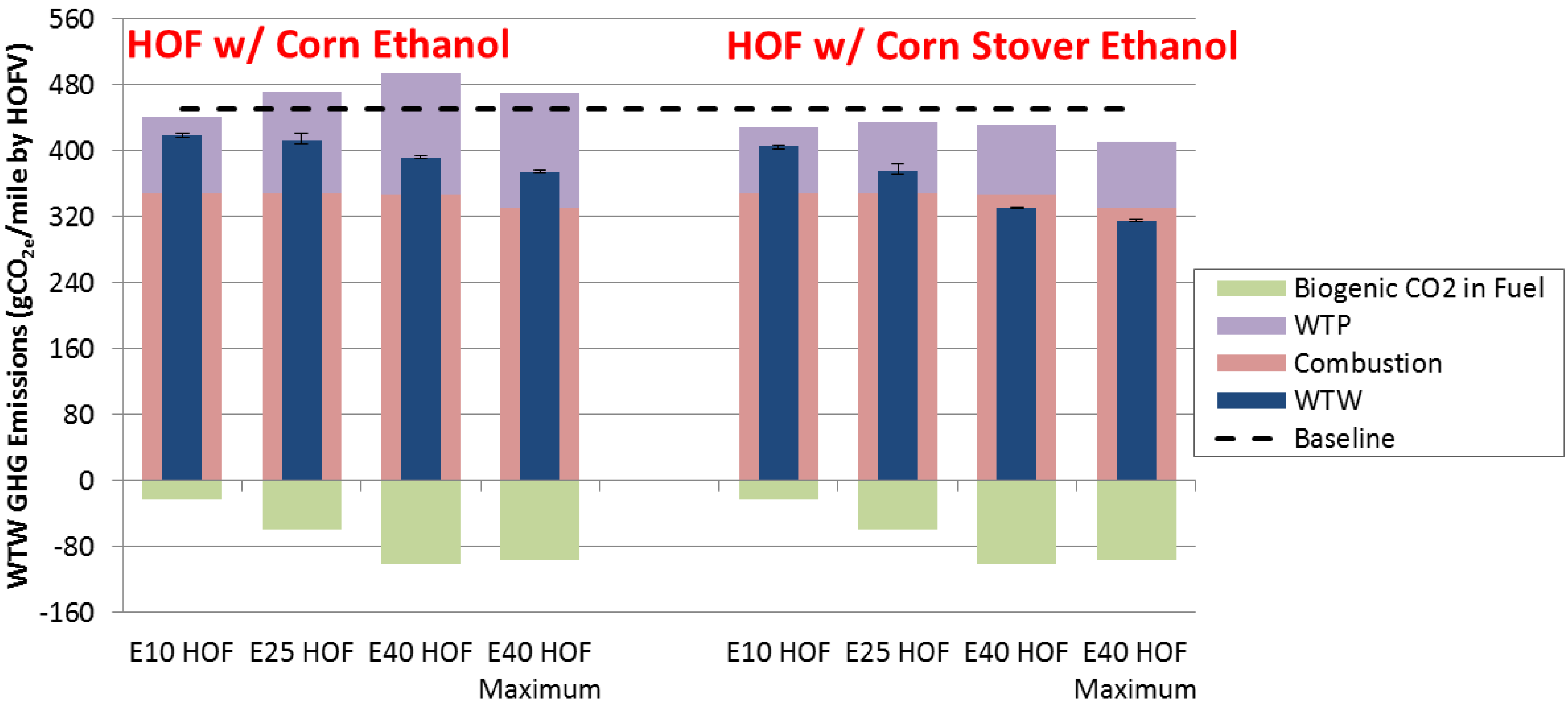
Finished HOF: higher ethanol blending level contributes to lower WTW GHG emissions of HOF (per MJ result, PADD3)



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

Vehicle fuel economy gains provides additional WTW GHG emissions reduction (per mile result, 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)

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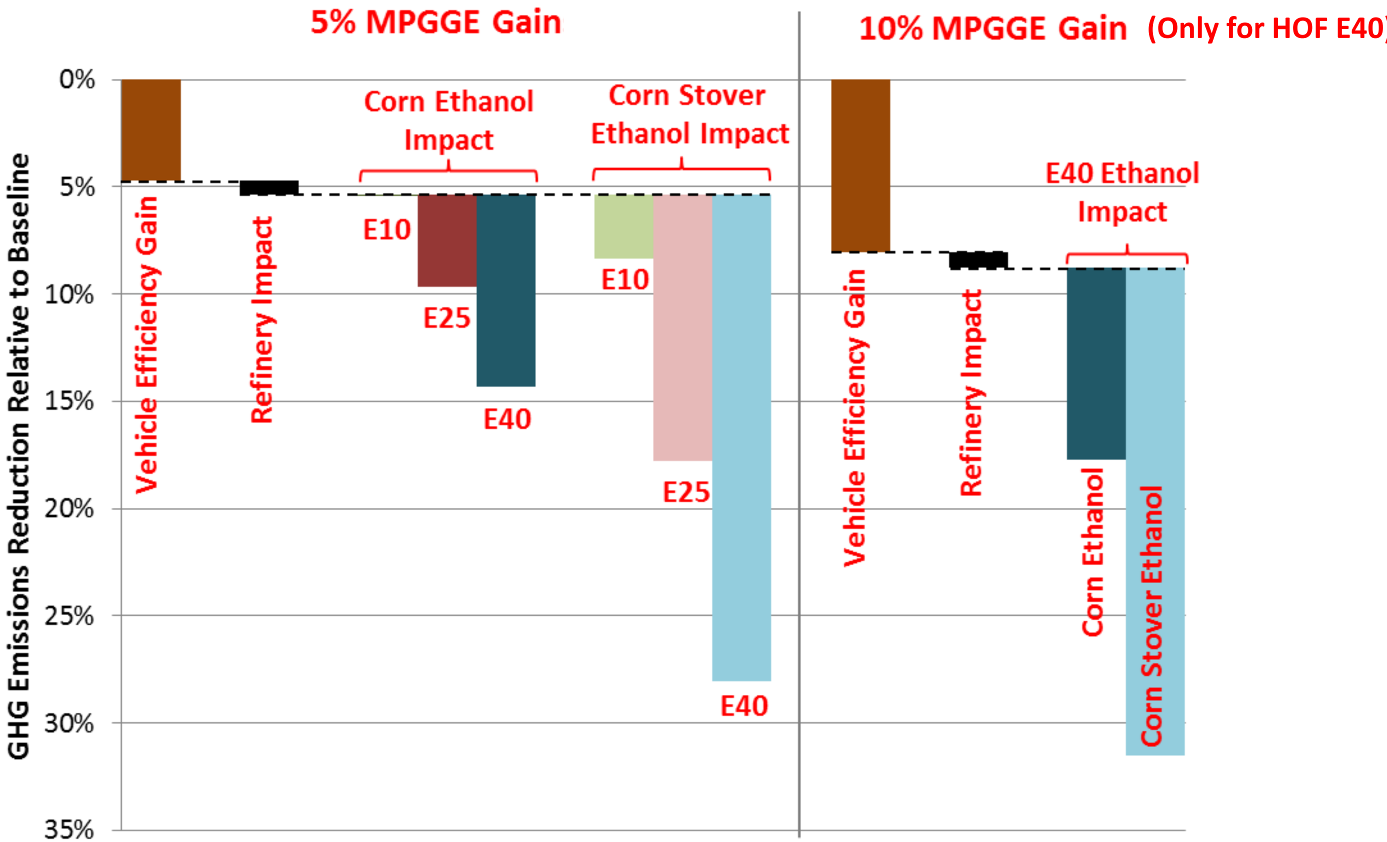
E25 and E40 HOF can reduce GHG emissions up to 17% and 31% relative to baseline gasoline, respectively



- Vehicle Efficiency Gain GHG effect: ~5% for 5% MPGGE gain, ~9% for 10% MPGGE gain
- Refinery Impact: <1%
- Ethanol Blending Impact
  - Corn Ethanol: 0% for E10, 4% for E25, 9% for E40
  - Corn Stover Ethanol: 3% for E10, 12% for E25, 23% for E40

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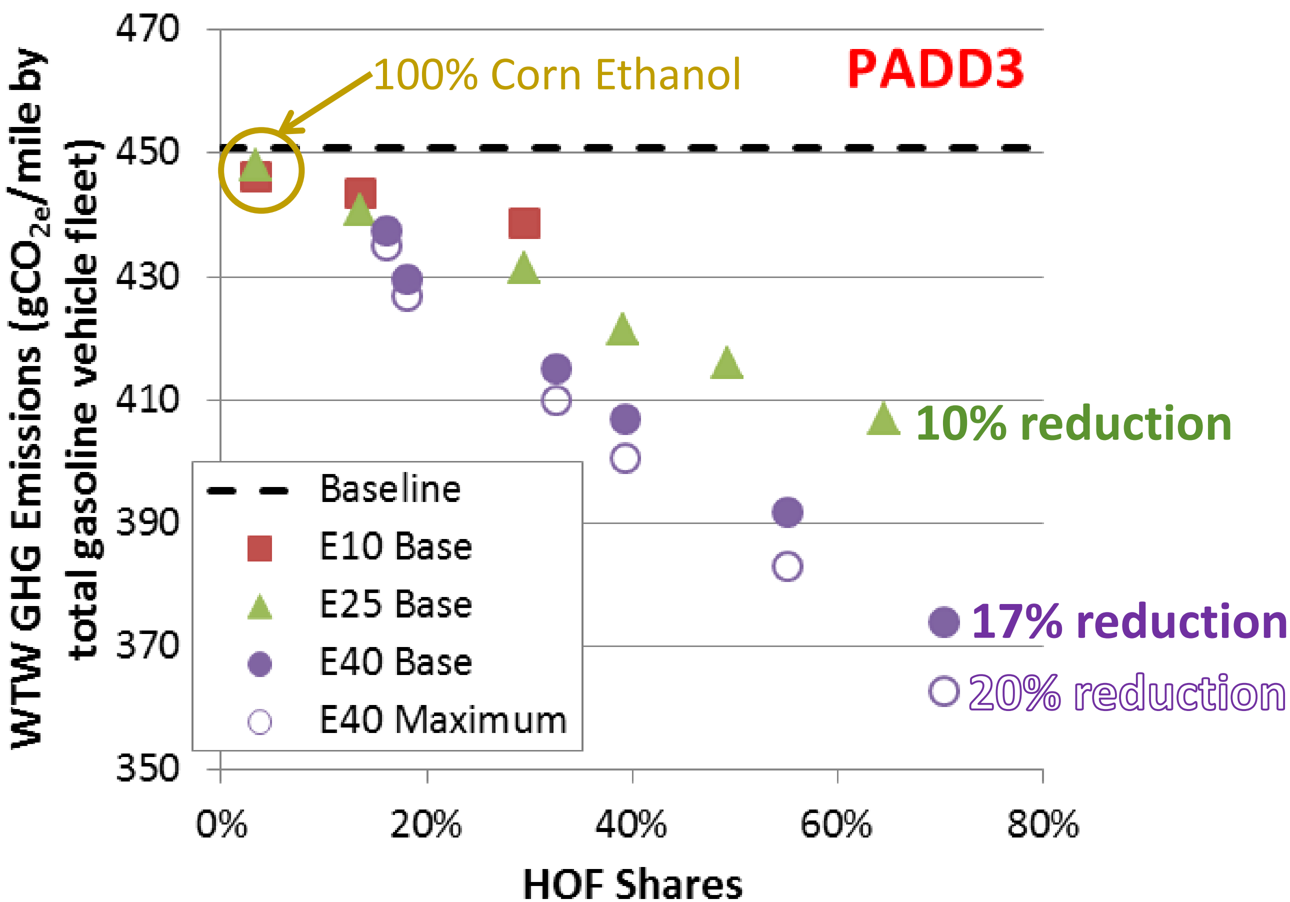
HOF impacts on GHG emissions by the complete gasoline vehicle fleet are diluted by regular gasoline ICEVs depending on HOF shares



- The complete domestic gasoline vehicle fleet: a mix of HOFVs and non-HOFVs
- Corn ethanol supply is limited at 15 billion gallons (balance comes from cellulosic ethanol)
- The ethanol demands can be satisfied by 100% corn ethanol in only the lowest HOF market shares (3.4%) with E10 and E25

Outline of Presentation

Tim - ORNL

- Project Planning & Communication – ORNL, NREL & ANL
- Demonstration of RSP performance in legacy FFVs – ORNL
- Dedicated RSP Vehicle Demonstration - ORNL

Bob - NREL

- Knock-resistance of ethanol blends - NREL
- Low-cost blendstocks - NREL
- Infrastructure assessment for RSP – NREL & ORNL
- Market assessment of RSP – NREL & ORNL

Jeongwoo - ANL

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

Tim – ORNL

- **Future Work & Summary**

Relevance

- Relevance to BETO
  - MYPP Barriers
    - It-F: Engine not optimized for biofuel
    - Im-H: Availability of biofuels distribution infrastructure
    - It-I: Lack of awareness and acceptance of biofuel as a viable alternative
    - At-B: Limitations of analytical tools and capabilities for system-level analysis
    - At-A: Lack of comparable, transparent, and reproducible analysis
  - Potential to displace >15 billion gal petroleum fuel
  - Introduce additional demand that allows for cellulosic ethanol and moves us past the blend wall

- Relevance to stakeholders
  - Ethanol/cellulosic biofuels industry – expands market
  - Car makers – fuels that enable more efficient engines
  - Societal – substantial GHG emission reductions; stable fuel prices
  - FFVs offer immediate bridge for this new fuel

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Expected Outcomes of RSP

- RSP does appear to offer significant benefits …
  - ✓ Ethanol is significant enabler for high octane fuels
  - ✓ Vehicle efficiency gains appear real (5-10% likely)
  - ✓ ~ 30% reduction in GHG with cellulosic ethanol
  - ✓ Little decrease in overall US refinery efficiency, even at very high demands
  - ✓ Ethanol offers refinery benefits not achievable with high octane E10
  - ✓ Allowing opportunities for refineries to export gasoline products
  - ✓ Immediately usable in 17M FFVs
  - ✓ Realistic path forward in infrastructure
  - ✓ Significant market share for dedicated RSP vehicles using different market scenarios
  - ✓ Significant increase in ethanol demand (past blend wall and allow cellulosic ethanol production)
  - ✓ With <u>equal</u> decreases in petroleum!

Future Work (9 months left)

- Communicate infrastructure path forward
- Can we use existing FFVs as an effective “bridge” to dedicated/optimized RSP vehicles?
- Conduct additional refinery LP modeling
- Investigate the upstream impacts of tight light oil
- Sensitivity analyses for RSP profitability – to the four stakeholder groups
- Improved feedback loops between vehicle adoption models and ethanol market models
- Estimate ethanol consumed through RSP
- Demonstrate efficiency gains in dedicated RSP vehicle
- Find approach/option that helps petroleum industry support RSP

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Summary

1. Overview → collect information on market viability of high-octane ethanol fuel blend (Renewable Super Premium)
2. Approach → 3-Lab collaboration with multiple technical topics considering end-end impact of RSP
3. Technical Accomplishments/Progress/Results
   - ✓ FFVs
   - ✓ Infrastructure
   - ✓ Low-cost blends
   - ✓ Knock-resistance
   - ✓ Refinery analysis
   - ✓ Dedicated RSP Vehicle
   - ✓ Market assessment
   - ✓ WTW GHG analysis
4. Relevance → RSP addresses improved fuel economy & increased consumption with significant environmental benefits
5. Future work → complete analyses, vet results, and demonstrate efficiency gains in dedicated RSP vehicle

Additional Slides

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Publications & Papers

- Chupka, G.M., Christensen, E., Fouts, L., Alleman, T.L., Ratcliff, M., McCormick, R.L. "Heat of Vaporization Measurements for Ethanol Blends Up To 50 Volume Percent in Several Hydrocarbon Blendstocks and Implications for Knock in SI Engines" SAE Technical Paper No. 2015-01-0763 (April 2015).

- Alleman, T.L., McCormick, R.L., Yanowitz, J. "Properties of Ethanol Fuel Blends Made with Natural Gasoline" *Energy and Fuels* submitted for publication.

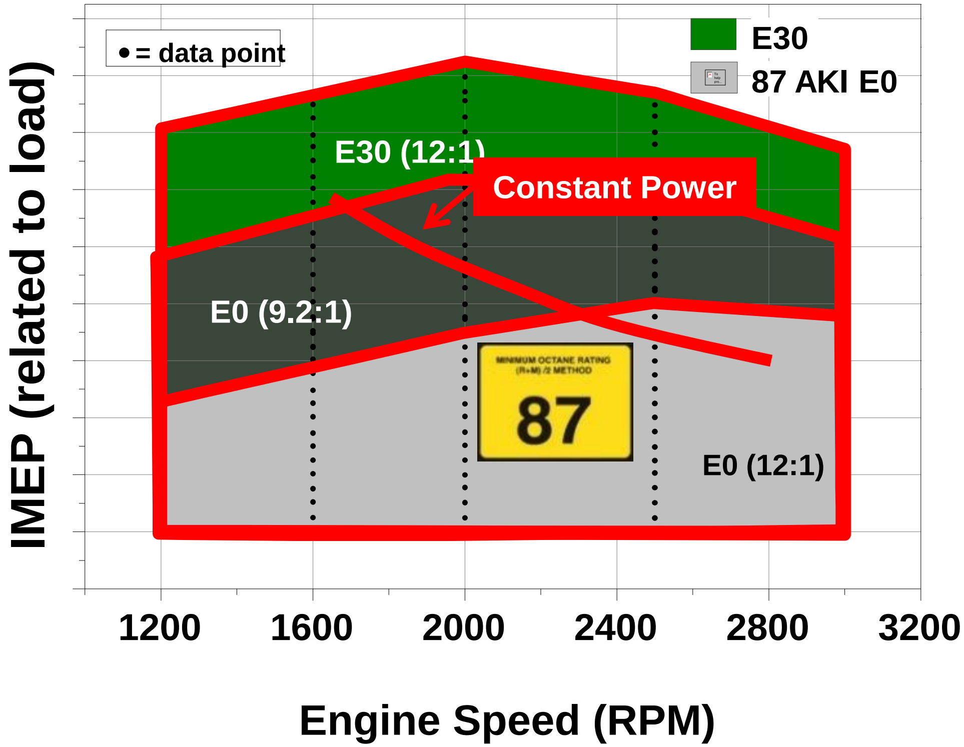
- Moriarty, K., Kass, M., Theiss, T. "Increasing Biofuel Deployment and Utilization through Development of Renewable Super Premium: Infrastructure Assessment" Technical Report, NREL/TP-5400-61684, November 2014.

Glossary

- BETO: Bioenergy Technologies Office
- BOB: Blendstock for Oxygenate Blending
- CAFE: Corporate average fuel economy
- CARBOB: California reformulated blendstock for oxygenate blending
- CBOB: Conventional blendstock for oxygenated blending
- DHA: Detailed hydrocarbon analysis
- DMT: Demonstration & Market Transformation
- DSC/TGA: Differential scanning calorimetry/thermogravimetric analysis
- EXX: XX% ethanol
- FFV: Flex-fuel Vehicle
- FTP: Federal Test Procedure
- HFET:
- HOF: High Octane Fuel
- HOV: Heat of vaporization
- GDI: Gasoline Direct Injection
- GHG: Greenhouse Gas
- GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
- ICEV: Internal Combustion Engine Vehicle
- KLSA: Knock Limited Spark Advance
- LP: Linear Programming
- MPGGE: Miles Per Gallon Gasoline Equivalent
- OUST: Office of Underground Storage Tanks
- OEM: Original Equipment Manufacturer
- PADD: Petroleum Administration for Defense District
- RON: Research Octane Number
- RSP: Renewable Super Premium
- RSPV: Renewable super premium vehicle
- RVP: Reid Vapor Pressure
- T&D: Transportation and Distribution
- US06:
- WTW: Well-To-Wheels
- VTO: Vehicle Technologies Office

Recent Studies Highlight 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 anti-knock index (AKI or Research Octane Number)
- Increased torque enables downspeeding and downsizing for improved fuel economy
  - Engine and system efficiency can balance lower energy density of ethanol blends



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

- Splitter and Szybist, ORNL

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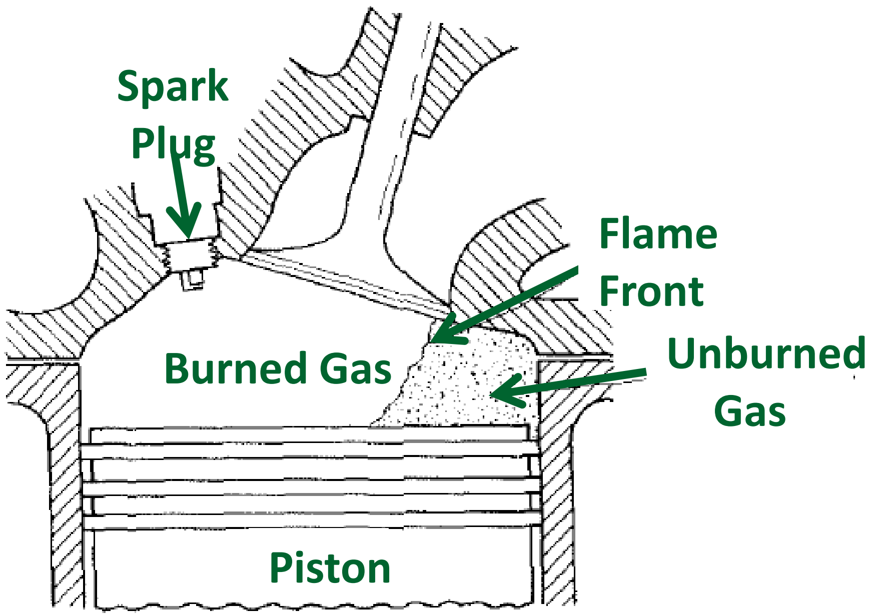
SI Engine Efficiency Limiting Factor: Engine Knock

- Knock occurs when unburned gas auto-ignites ahead of the flame front
- The unburned gas temperature and pressure become too high for the knock resistance of the fuel
- Strategies to increase efficiency increase temperature and pressure
- Solutions:
  - Higher octane number
  - Fuel evaporative cooling
  - Faster flame speed



Approaches to Increasing SI Engine Efficiency

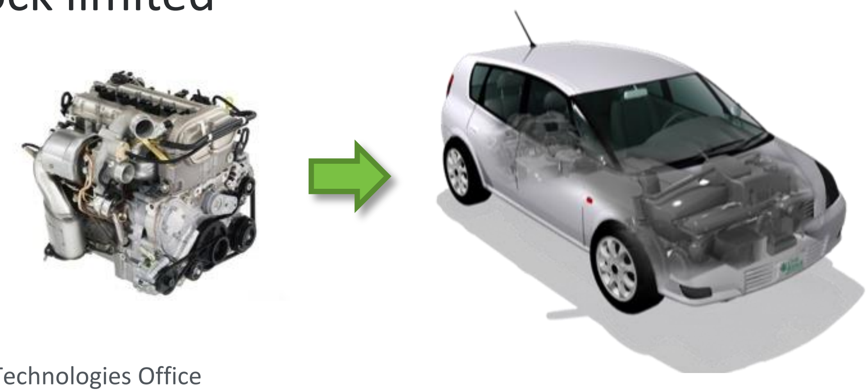
- Increased compression ratio
  - Greater thermodynamic efficiency
- Engine downsizing/downspeeding
  - Smaller engines operating at low-speed and higher load are more efficient
  - Optimized with 6 to 9 speed transmission
- Turbocharging
  - Recovering energy from the engine exhaust
  - Required for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

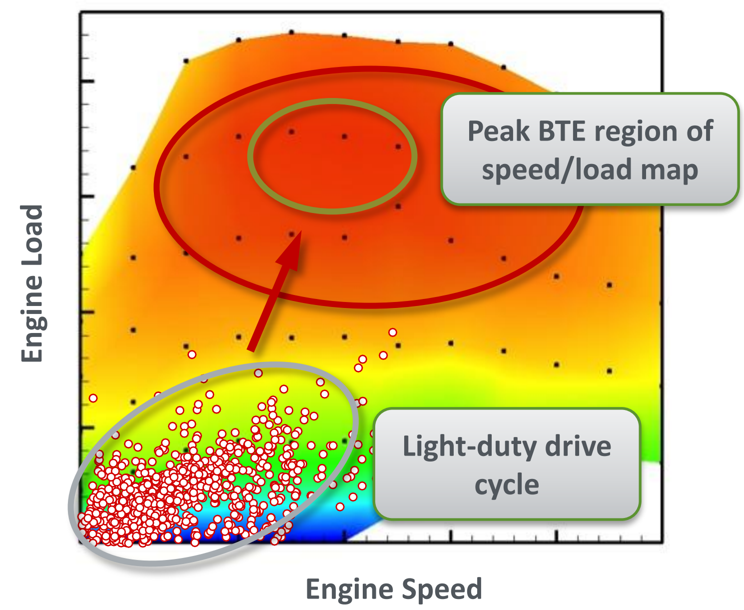
Enabled by knock resistant fuel

Advantage for ethanol

Mismatch in drive-cycle and highest engine efficiency is an opportunity

- Conventional direct-drive systems do not make use of highest engine efficiency
- Opportunity to shift engine drive-cycle demands to higher efficiency region
  - Hybridization is potential solution to de-couple drive cycle from speed/load demands
  - Down-speeding and down-sizing (e.g., cylinder deactivation, Ford EcoBoost)
- New technologies will help increase the size of the high efficiency plateau
- Higher octane fuels allow more operation in the highest efficiency plateau when engine is "knock limited"





High fuel efficiency region of current passenger vehicle production engines is small and does not intersect light-duty drive cycle speed/load requirements.

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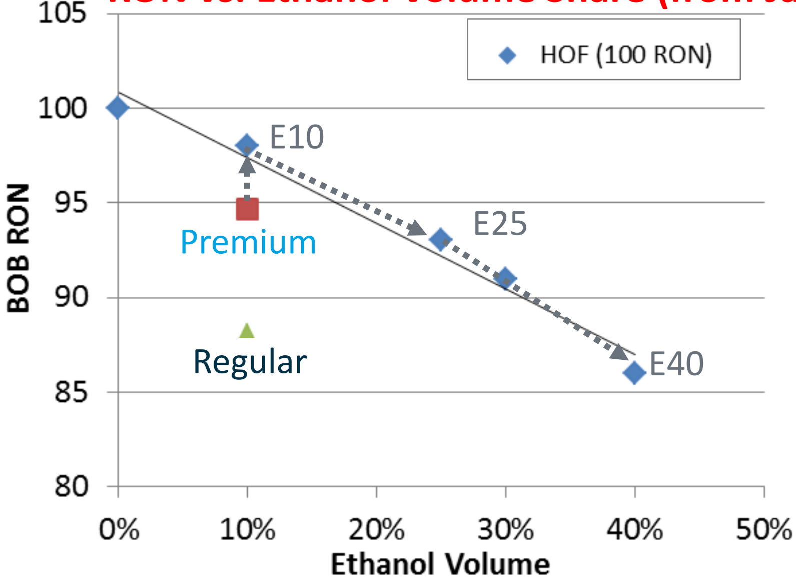
Research Octane Number (RON) and Reid Vapor Pressure (RVP) are key fuel specifications

	Regular gasoline (E10)	Premium gasoline	HOF E10	HOF E25	HOF E40
Fuel RON	91	96	100	100	100
BOB RON*	88 – 89	93 – 94	98	93	86
CG Summer RVP (psi)†	9	9	9	**8**	**8**
CBOB Summer RVP (psi)*	7.8	7.8	7.8	7.0	6.8
RFG Summer RVP (psi) †	**7**	**7**	**9**	**7**	**7**
RBOB Summer RVP (psi)*	5.6	5.6	**7.8**	5.7	5.1

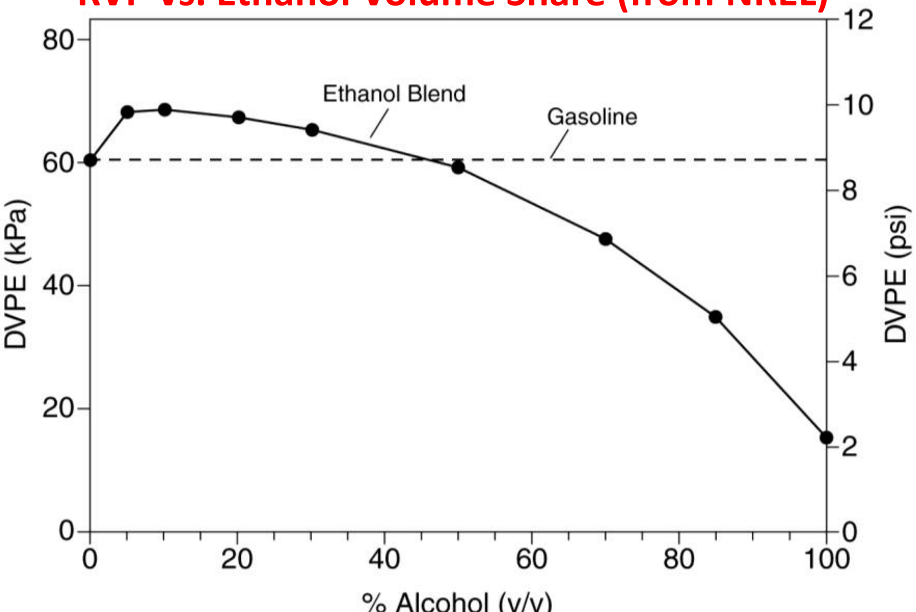
* BOB RONs and RVPs are estimated by Jacobs using formulae agreed by ANL, NREL and Jacobs

† Gasoline RVPs are determined through internal discussion among ANL, NREL and Jacobs

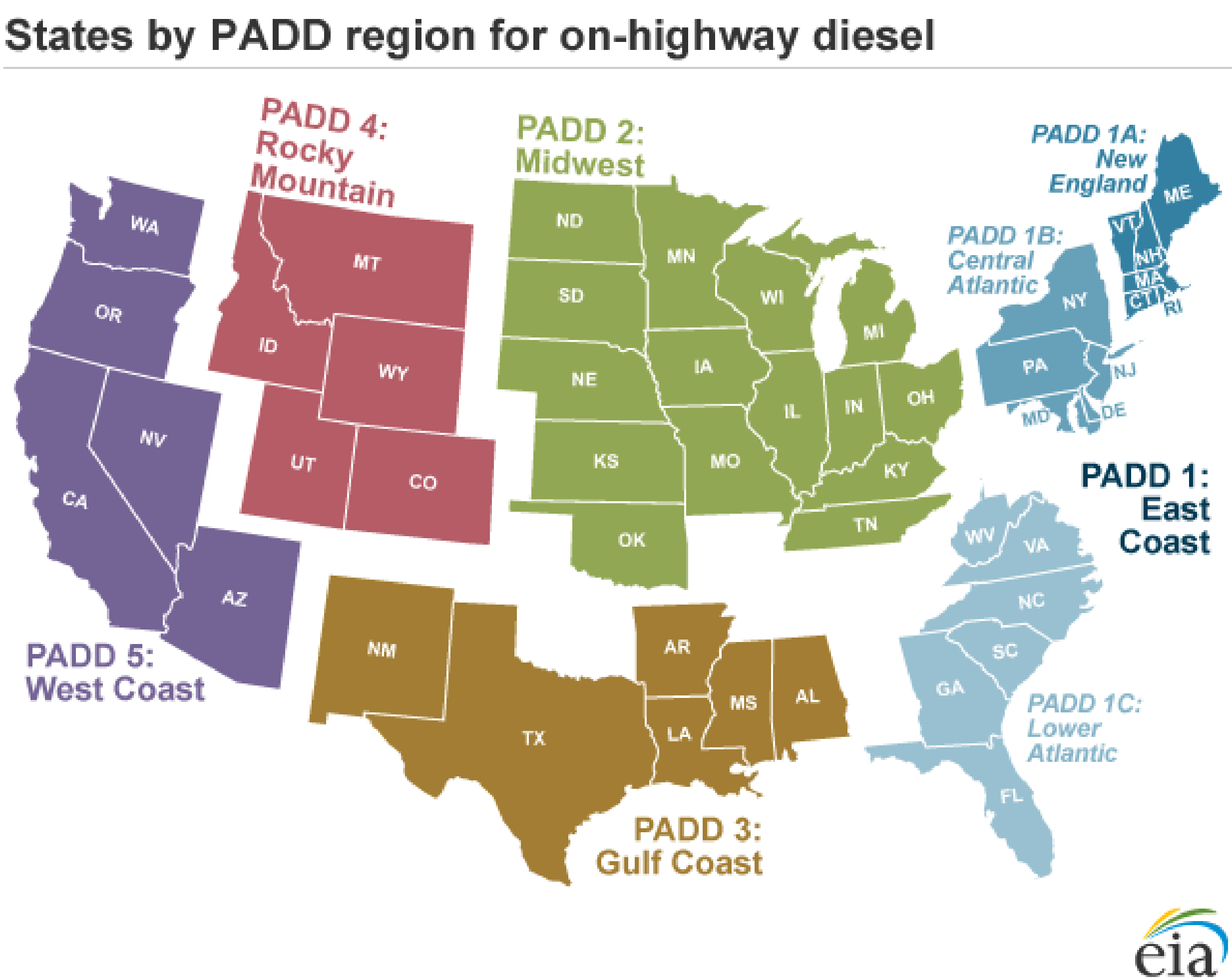
RON vs. Ethanol Volume Share (from Jacobs)



RVP vs. Ethanol Volume Share (from NREL)

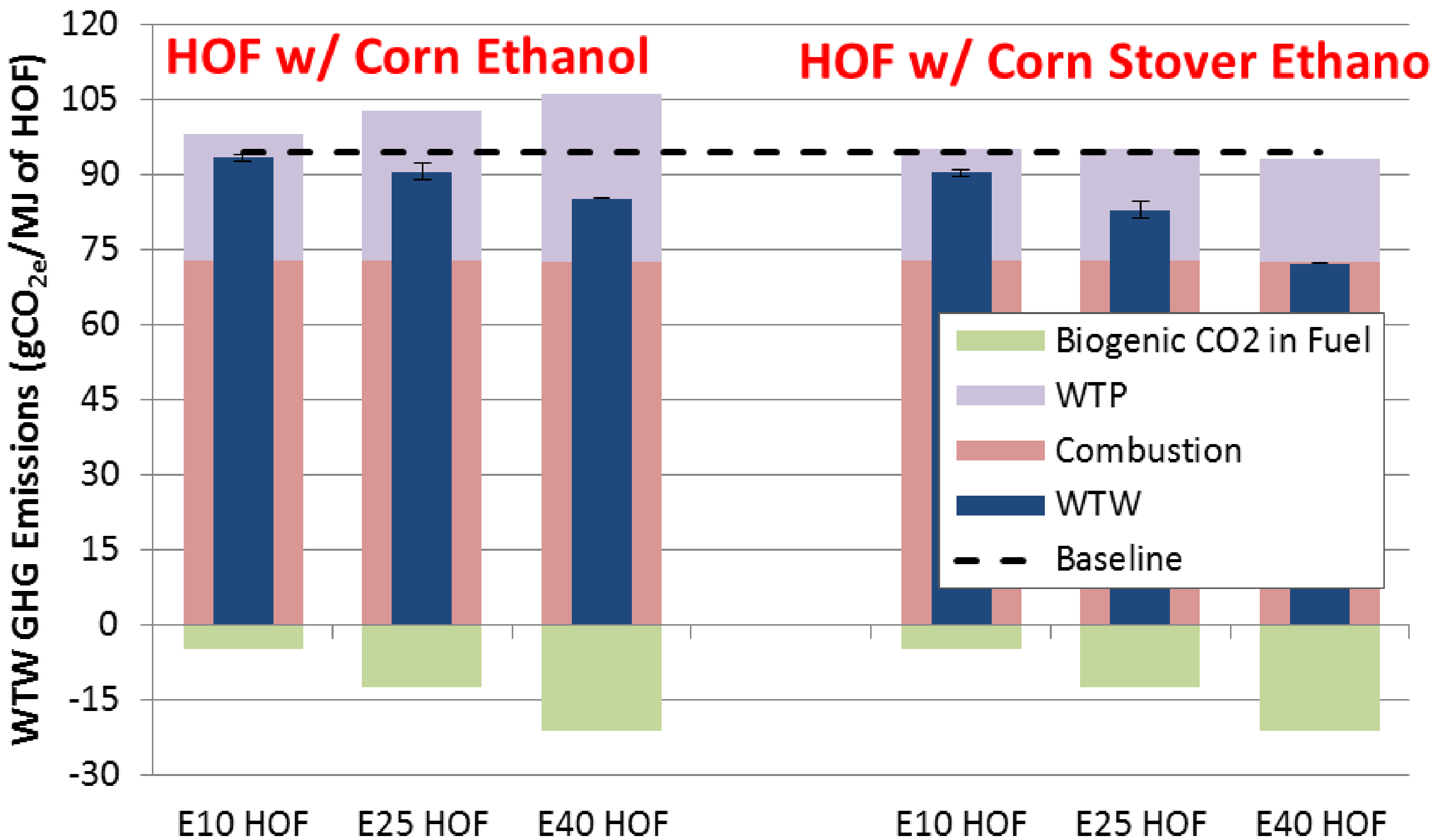


Petroleum Administration for Defense Districts (PADD)



PADD - Petroleum Administration for Defense Districts
U.S. Energy Information Administration Form EIA-888

Higher ethanol blending levels is key for WTW GHG emissions of HOF per MJ (PADD2)



- Corn stover ethanol is used as a surrogate for cellulosic ethanol
  - Corn stover ethanol provides much larger benefits

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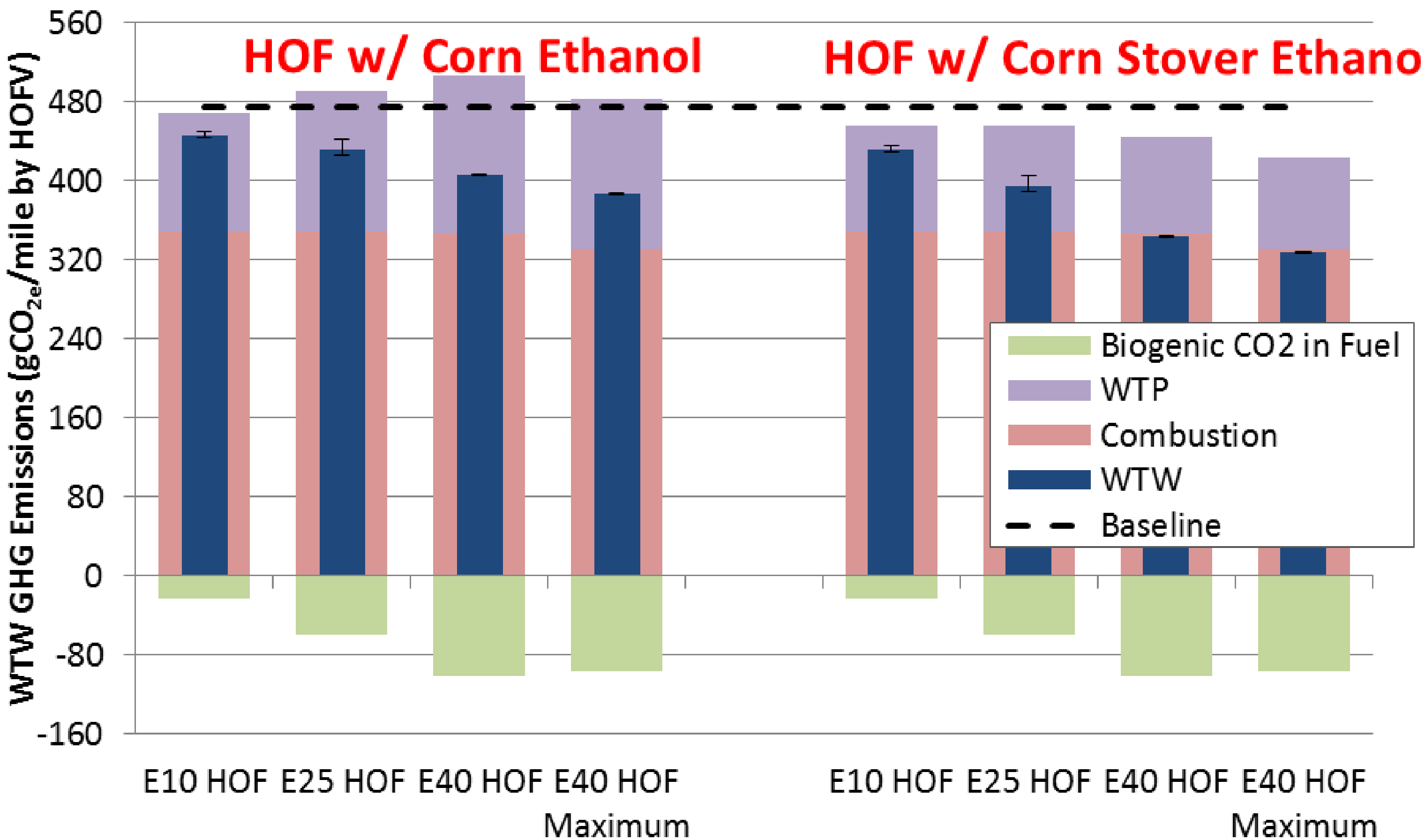
Vehicle fuel economy gains provides additional WTW GHG emissions reduction (per mile basis, PADD2)



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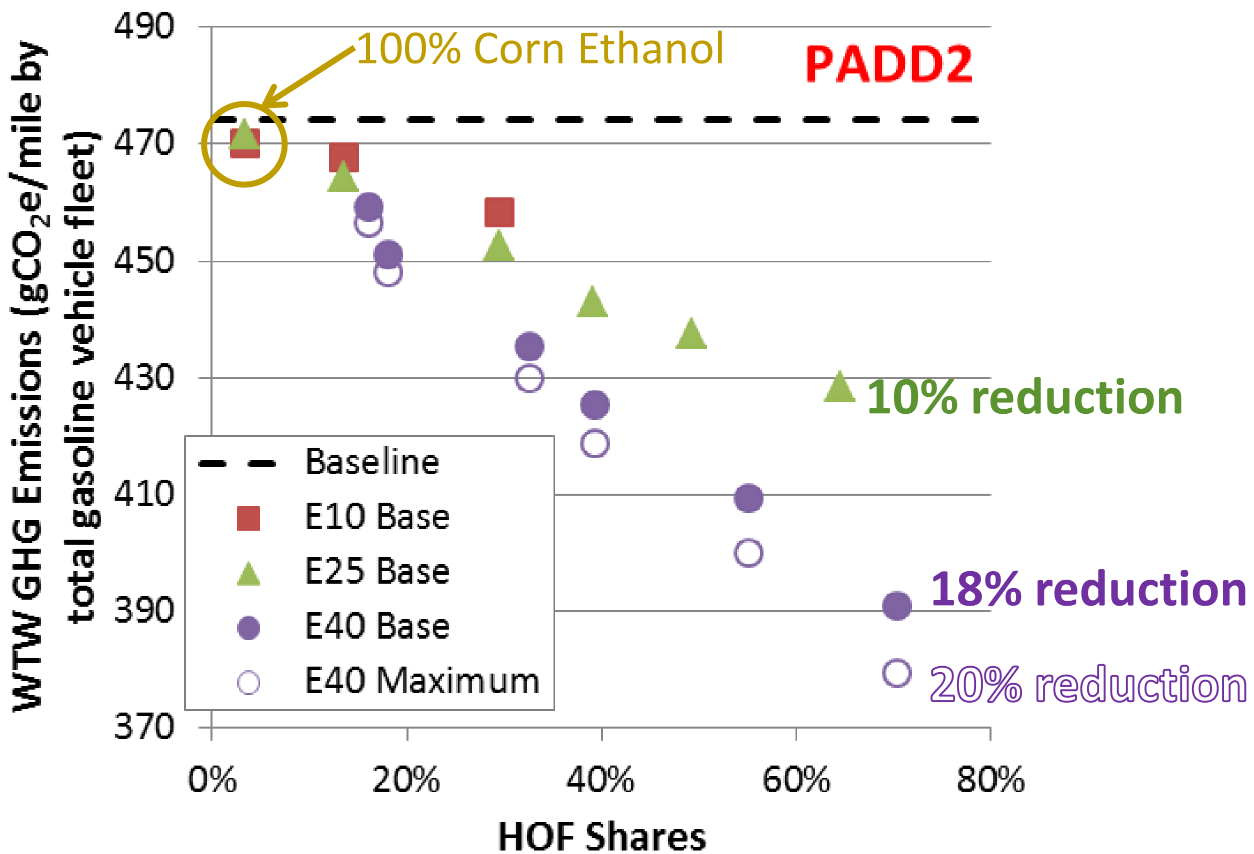
HOF impacts on GHG emissions by complete gasoline fleet are diluted by regular gasoline ICEVs depending on HOF shares



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