Refinery Study and Well-to-Wheels Analysis of Higher Octane Ratings for U.S. Gasoline

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Research and
Advanced Engineering

Background

Increasingly challenging requirements for light duty vehicles

- GHG emissions and fuel economy
- Emissions (PM, NOx, hydrocarbons, …)
- Safety
- Performance
- Content

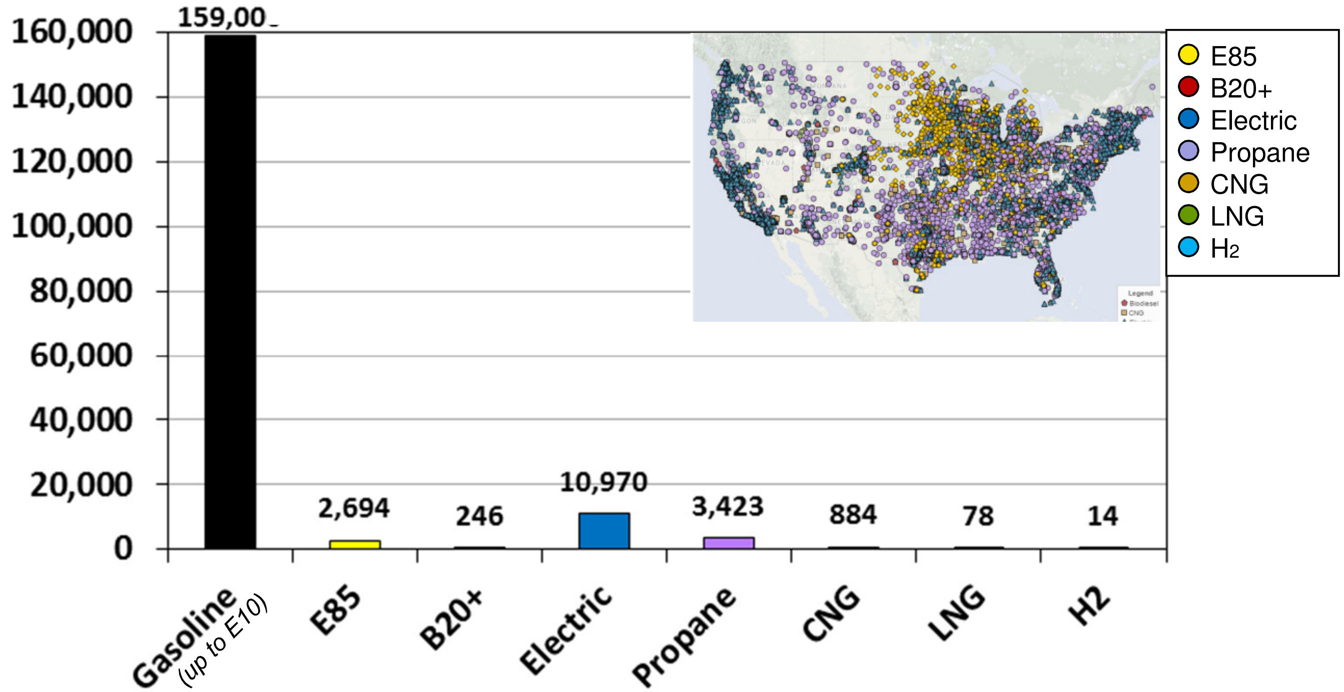
Fuel properties and composition have been changed over time to enable emissions reductions

- Tetraethyl lead removal
- Low sulfur (diesel, gasoline)
- Low RVP

GHG reductions require similar (or greater) support from fuels: higher octane and ultimately lower fossil carbon

Infrastructure

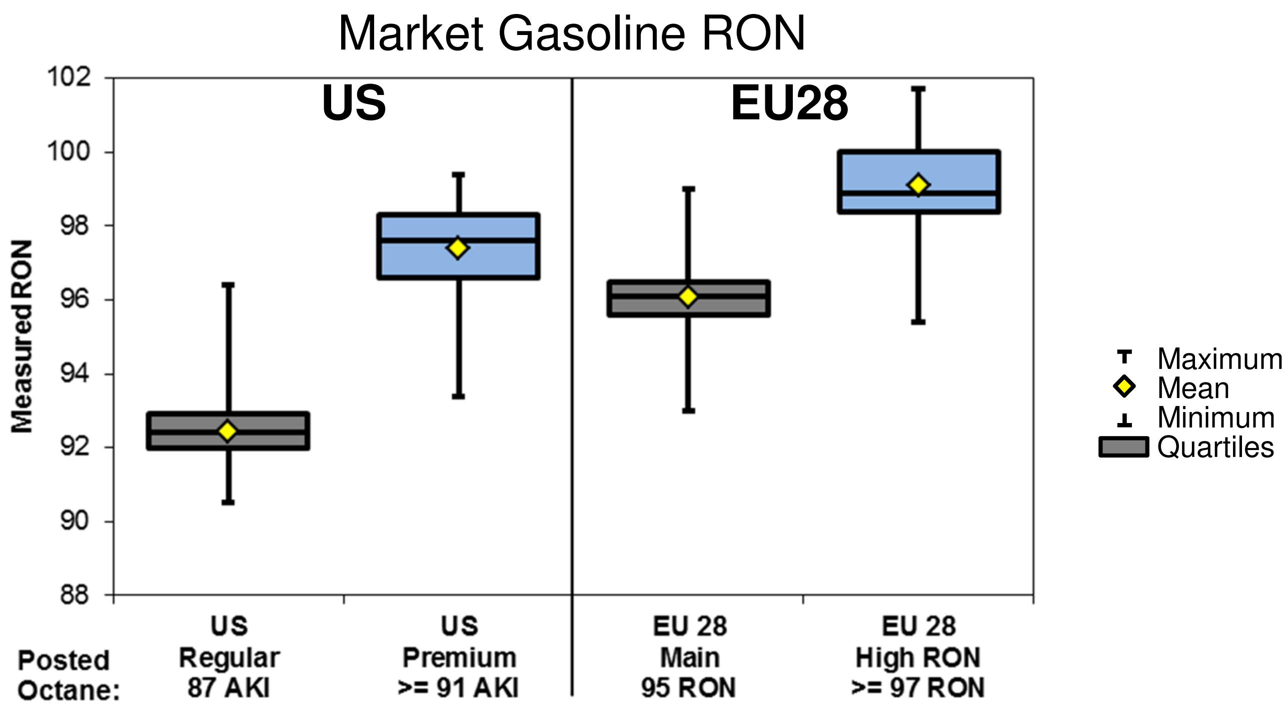
~160,000 public filling stations in the U.S.
~7,000 provide an alternative fuel
~3,000 locations provide an alternative liquid fuel



Source: U.S. DOE Energy Efficiency & Renewable Energy, Alternative Fuels Data Center, http://www.afdc.energy.gov/locator/stations, October 10, 2015

Higher gasoline octane ratings are an opportunity to improve engine efficiency with the most widely available fuel

National and Global Variation of Fuel Octane Ratings

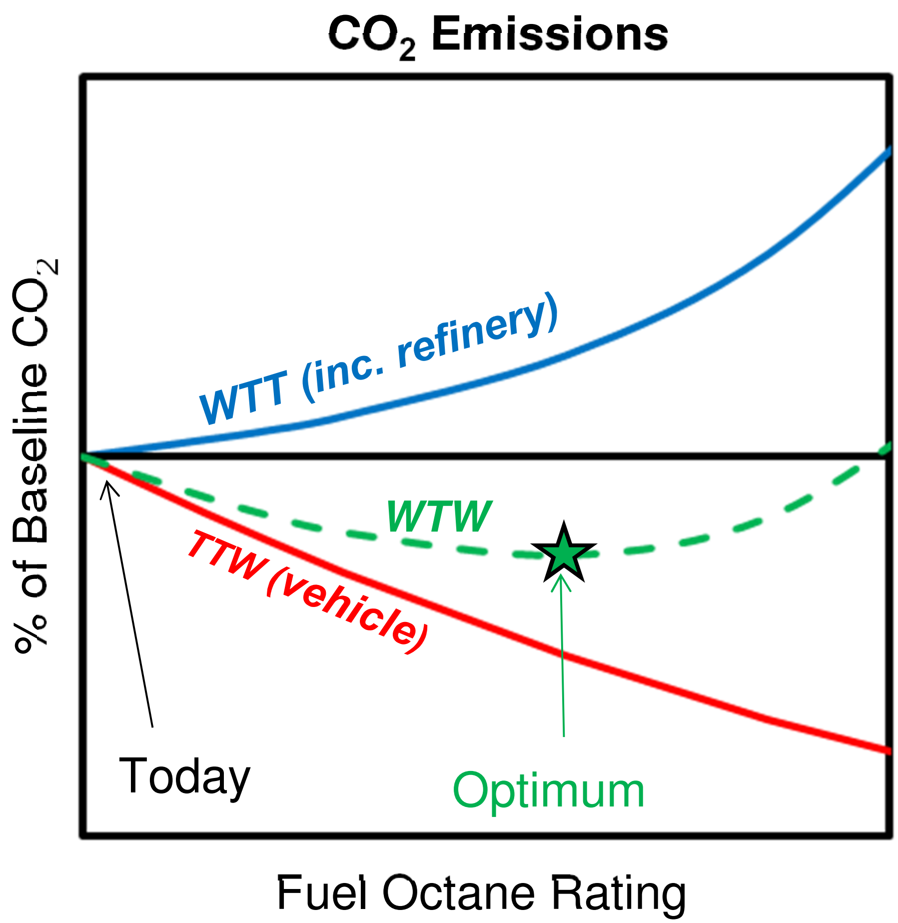


Market share: ~85% ~10% ~90% ~10%

Sources: SGS Worldwide Summer 2014 and Winter 2014 Fuel Surveys; Alliance of Automobile Manufacturers' North American Winter 2014 and Summer 2014 Fuel Surveys; Energy Information Agency

Lowest mainstream US gasoline RON limits engine compression ratios. Higher minimum market RON provides engine efficiency gain potential.

Higher Octane Gasoline Considerations



Higher octane fuel enables higher engine efficiency, but may increase refinery GHG emissions.

Key question:

Engine benefit vs. fuel cost

Well-to-wheels (WTW) analyses are needed to identify "optimum" octane ratings (CO$_2$, oil, cost, …)

Vehicle efficiency gains for higher-octane fuel can outweigh fuel production impacts, yielding net WTW reductions in CO_2 emissions

Well-To-Wheels Analyses Of Gasoline Octane Ratings

Well-to-Wheels = **Well-to-Tank** + **Tank-to-Wheels**

- **1970s US** (Amoco, Exxon) No oxygenates [1,2]
- **1980 Europe** (CONCAWE) No oxygenates [3]
- **2005 Japan** (JCAPII) Up to E3 [4]
- **2013 Europe** (CONCAWE) Up to E10, refinery only [5]
- **2014 US** (MIT) Up to E20, up to 100 RON [6]
- **2015 US** (ANL) Up to E40, 100 RON [7]
- **2015 US** (USCAR) E10-E30, up to 102 RON [8]

1. Wagner, SAE Technical Paper 730552, 1973.
2. Brown, Oil & Gas Journal, 29(9):125, 1974.
3. CONCAWE, The rational utilization of fuels in private transport (RUFIT), extrapolation to unleaded gasoline case. Report No. 8/80, 1980.
4. Japan Clean Air Program II (JCAPII), Study on CO2 from automobiles and refineries, June 1, 2005.
5. CONCAWE, Oil refining in the EU in 2020, with perspectives to 2030, Report No. 1/13R, 2013.
6. Speth et al., “Economic and Environmental Benefits of Higher-Octane Gasoline”, Environmental Science & Technology, 48(12):6561, 2014.
7. Argonne National Laboratory, “Well-to-wheels Analysis of High Octane Fuels”. ANL/ESD-15/10, July 14, 2015.
8. USCAR, “Well-to-Wheels Analysis of Higher Octane Ratings and Ethanol Content for Future U.S. Gasoline”, manuscript in preparation, 2015

New considerations such as higher ethanol blends and engine advancements have driven the need for new WTW analyses

USCAR Studies

Little data available on **refinery impacts**
→ Refinery study initiated with MathPro Inc.

Policy Analysis

pubs.acs.org/est

Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content

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Many papers on **engine efficiency** impacts have been published
→ Critical literature review conducted.

Critical Review

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The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency

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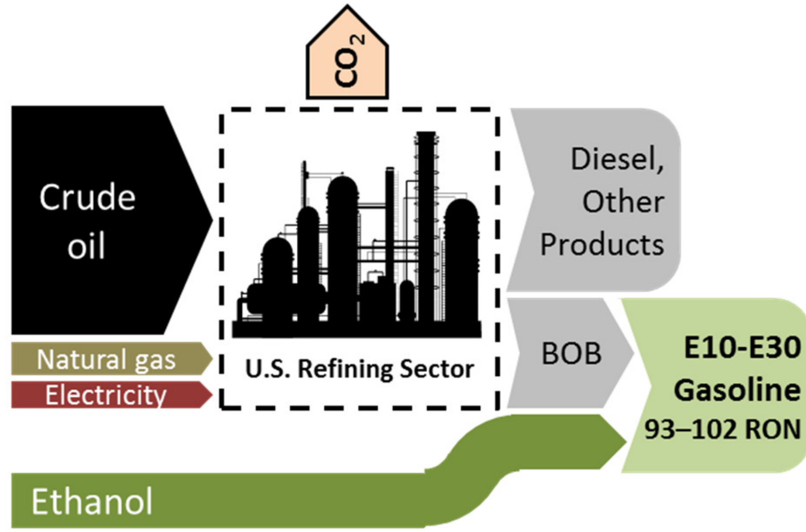
WTW analysis has been conducted; report is now being written for publication

Refinery Model

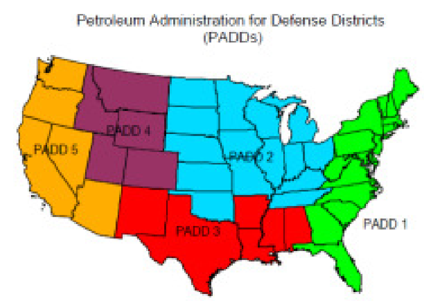
Approach

A regional refinery model was used to estimate effects on the U.S. refining sector for various combinations of prospective national RON standard (92 to 102 RON), ethanol content and blending approach (E10, E20, E30, E10+E85).



Linear programming (LP) model covering U.S. as three regions, two seasons

- PADDs 1,2,3 as single region; PADD 4; PADD 5



Refinery LP models identify least-cost refinery operation configurations that meet given requirements and constraints.

Key assumptions

- Investments allowed
- Petroleum product volume projections for 2017 from U.S. DOE EIA AEO2012, maintained for all cases
- Oil $96/bbl, natural gas $5.20/mcf (AEO2012)

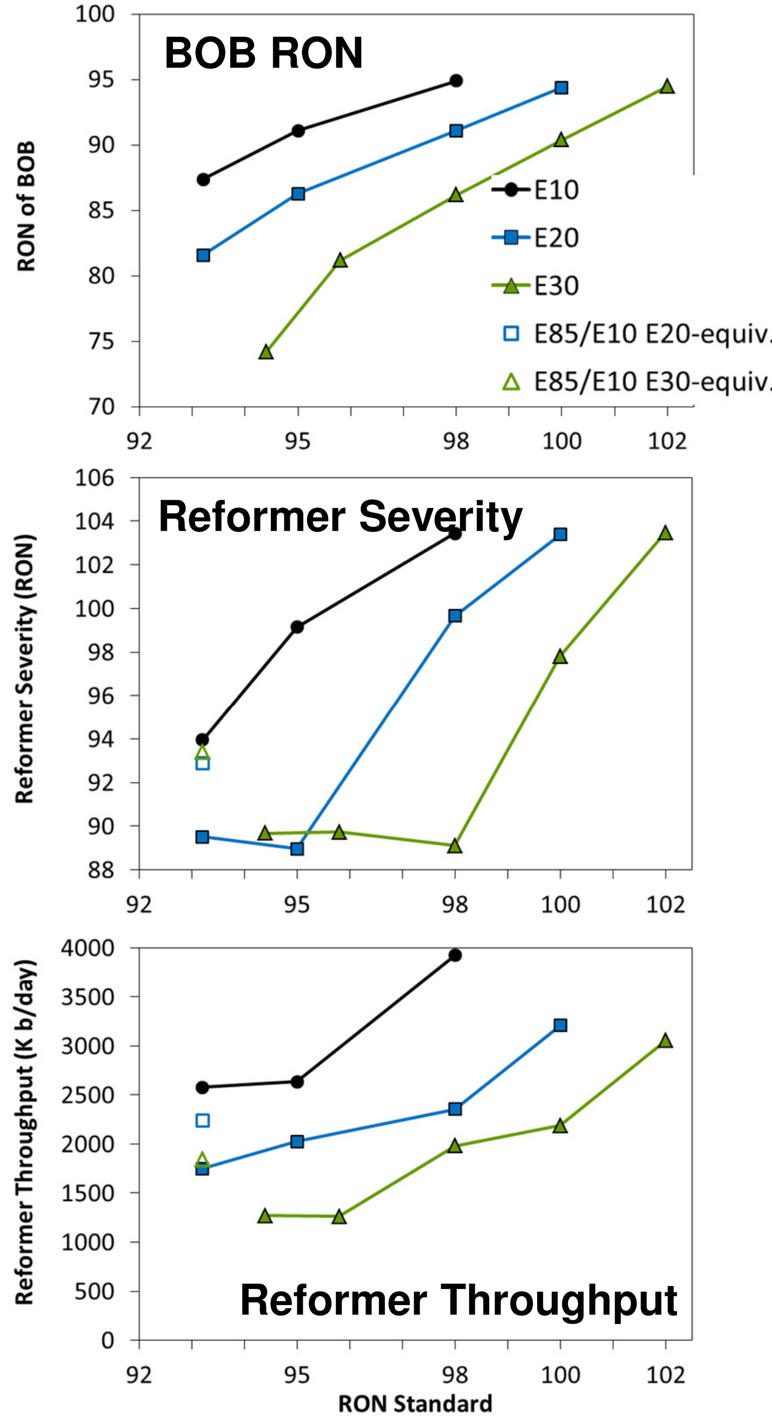
MathPro

Refinery Model – BOB Impacts

- Higher octane rating fuels require (for equal Exx)
  - Higher BOB RON
  - Increased reformer severity, throughput

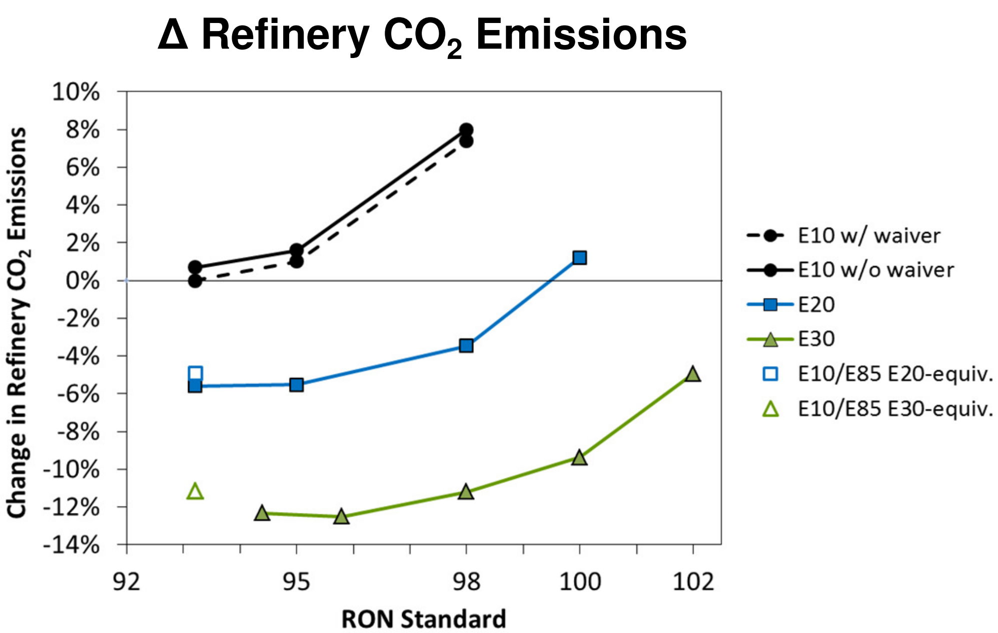
- Higher ethanol content fuels lead to… (for equal RON fuel)
  - Lower BOB volumes
  - Lower BOB RON
  - Reduced reformer severity, throughput

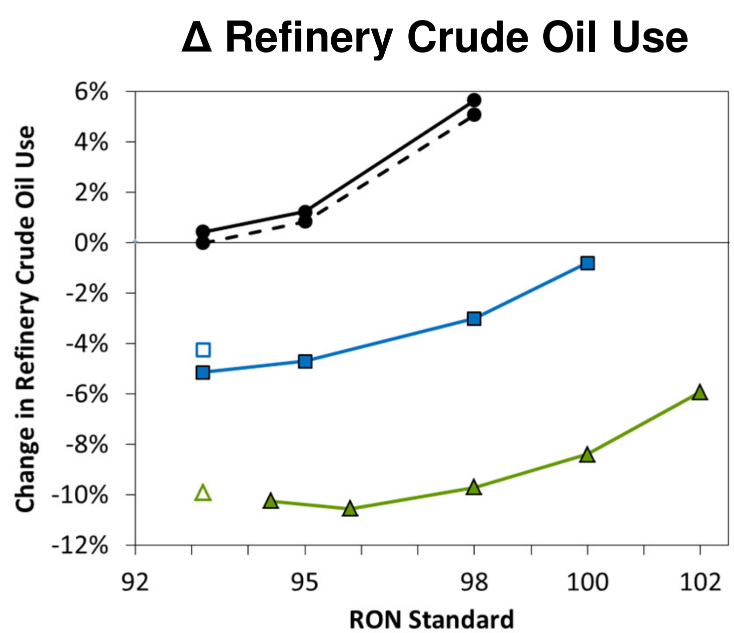
- Cases requiring BOBs with >95 RON were considered infeasible



Refinery Model – CO_2 Emissions, Crude Oil

- Increase with higher RON (1-2% for 95 RON E10 or 98 RON E20-E30)
- Decrease with higher ethanol content
- E85+E10 options slightly higher than 93-RON midlevel blends





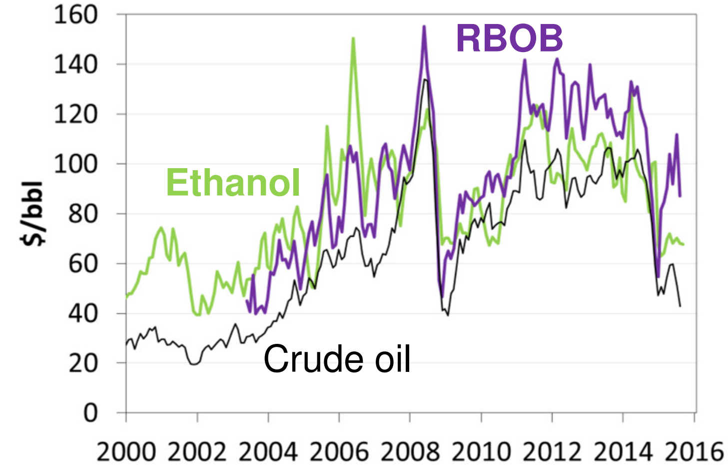
Possible opportunity for higher RON with E10 or midlevel blends

Refinery CO_2 emissions and crude oil use include those for producing all products (gasoline, diesel, etc.)

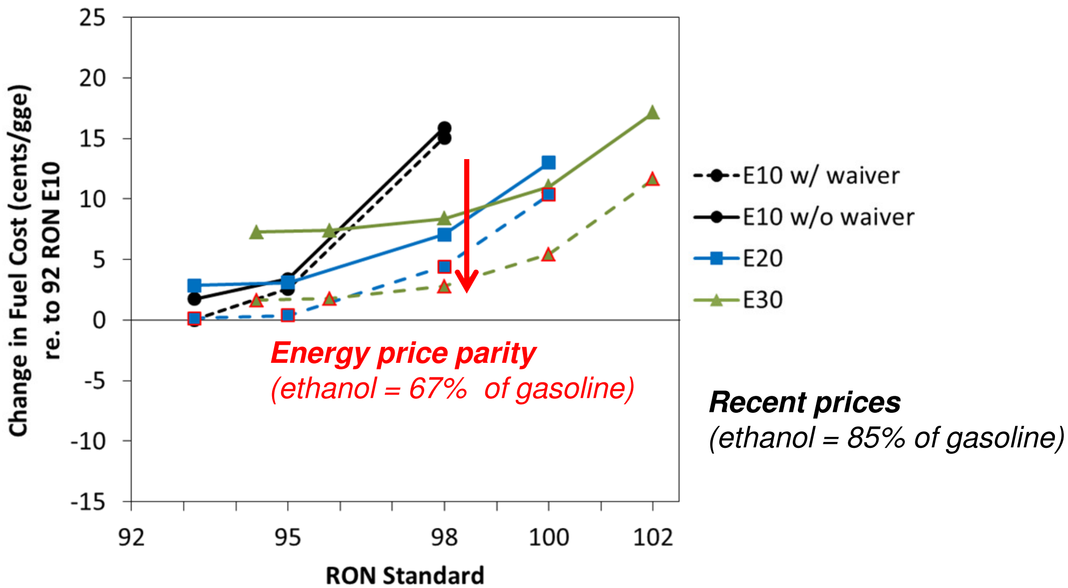
Refinery Model – Cost

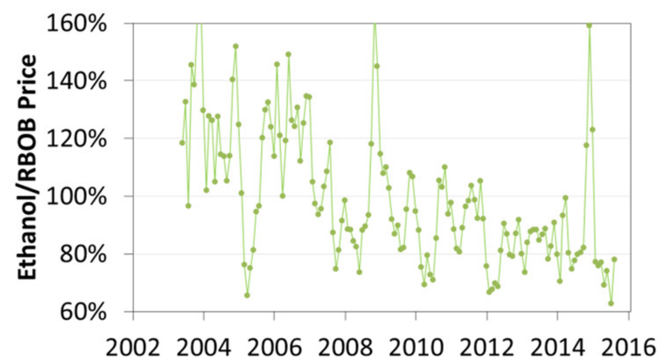
Fuel production cost

- Primary factor: Costs of ethanol and crude oil
- Secondary factor: RON



Δ Fuel Cost at Terminal (¢/gge)
(rel. to 93 RON **E10**)





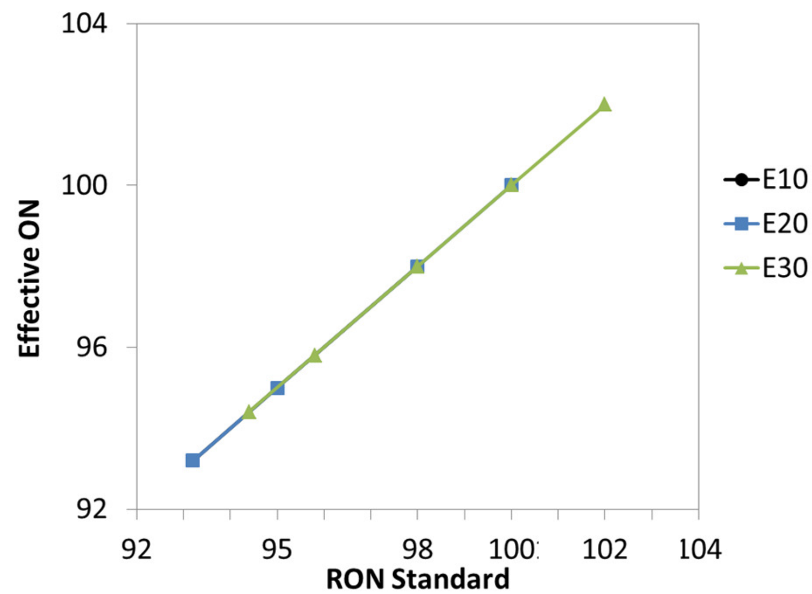
Oil = $96/bbl

Possible opportunity for higher RON with E10 or midlevel blends

Engine Efficiency Model

1. Fuel knock resistance (DI,GTDI)

- RON
- Evaporative cooling
  - E0-E40 : fully included in RON*
  - E40+ : 1.6 ON** per 10%v ethanol (on amount above E40)



Model documented by Leone et al., Environ. Sci. Technol. 49(18):10778 (USCAR: Ford, GM, FCA)

** Foong et al., SAE Int. J. Fuels Lubr. 6(1):34, 2013 (Univ. of Melbourne)*

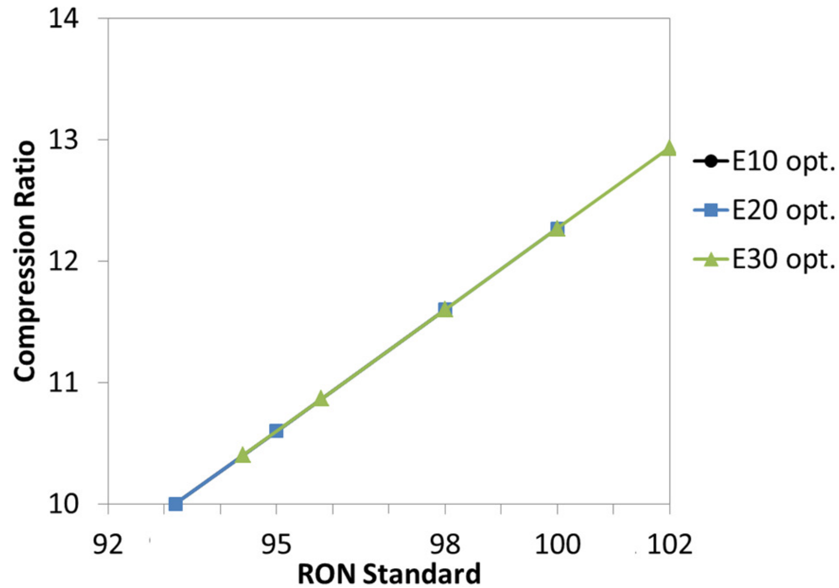
Leone et al., SAE 2014-01-1228 (Ford)

*** Kasseris, SAE 2012-01-1284 (MIT)*

Engine Efficiency Model

2. Engine CR increase

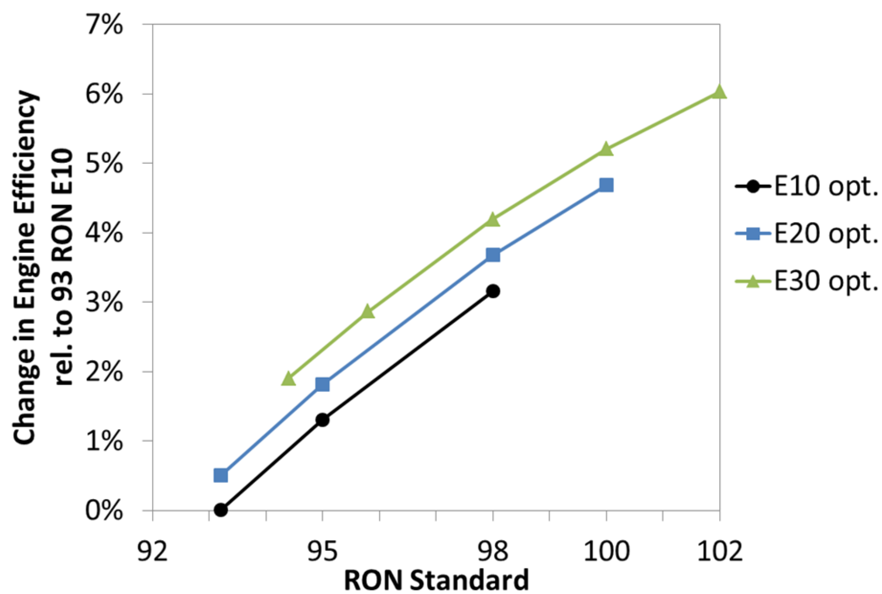
- Baseline CR 10:1 GTDI
- 3 ON enables 1 CR[#]
  - *Literature: 2.5 to 9 ON/CR, 2.8 in Ford GTDI studies**



3. Engine efficiency increase

- CR effect
- Part-load effects[#,**]: +0.5% eff'y per 10%v ethanol

Engine assumption: GTDI



[#] Leone et al., Environ. Sci. Technol. 49(18):10778.
** Jung et al., SAE 2013-01-1321*
Leone et al., SAE 2014-01-1228
*** Jung et al., SAE 2013-01-1634*

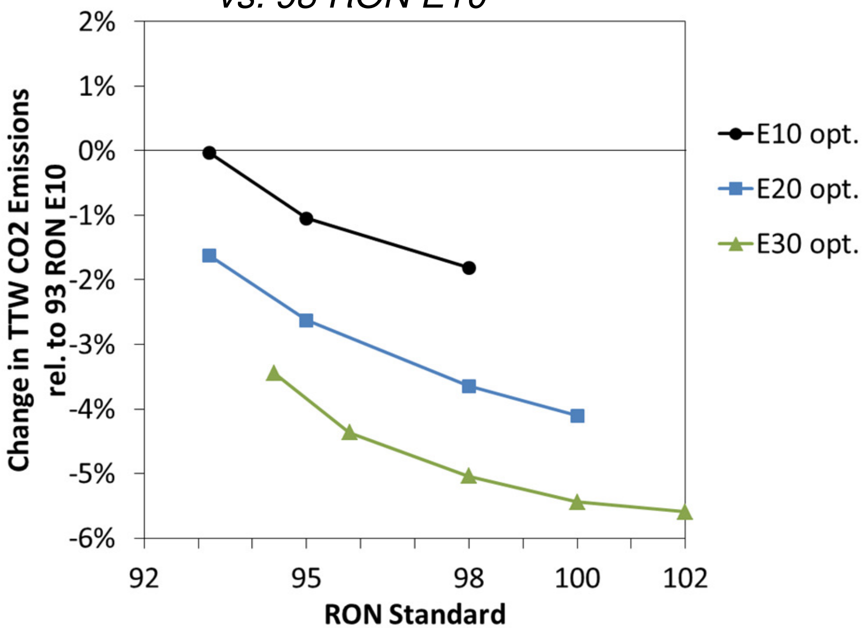
Engine Efficiency Model and CO_2 Emissions

4. Engine CO_2 emissions

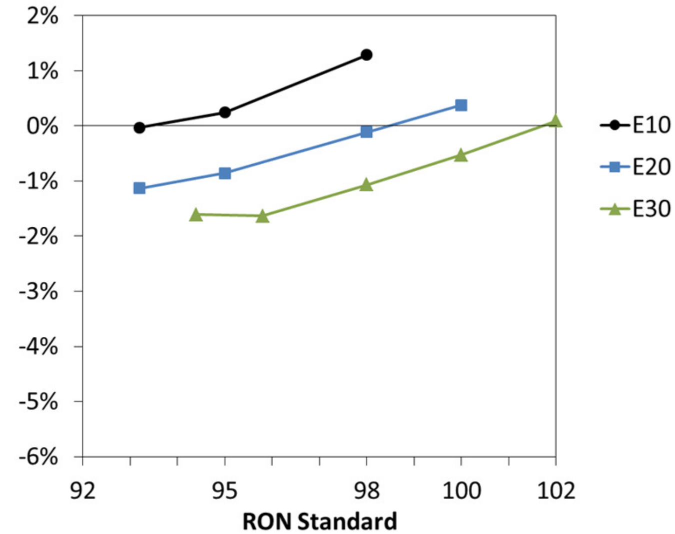
- Engine efficiency
- Fuel carbon intensity (C wt% / LHV)

Δ Tailpipe CO_2 Emissions

vs. 93 RON E10



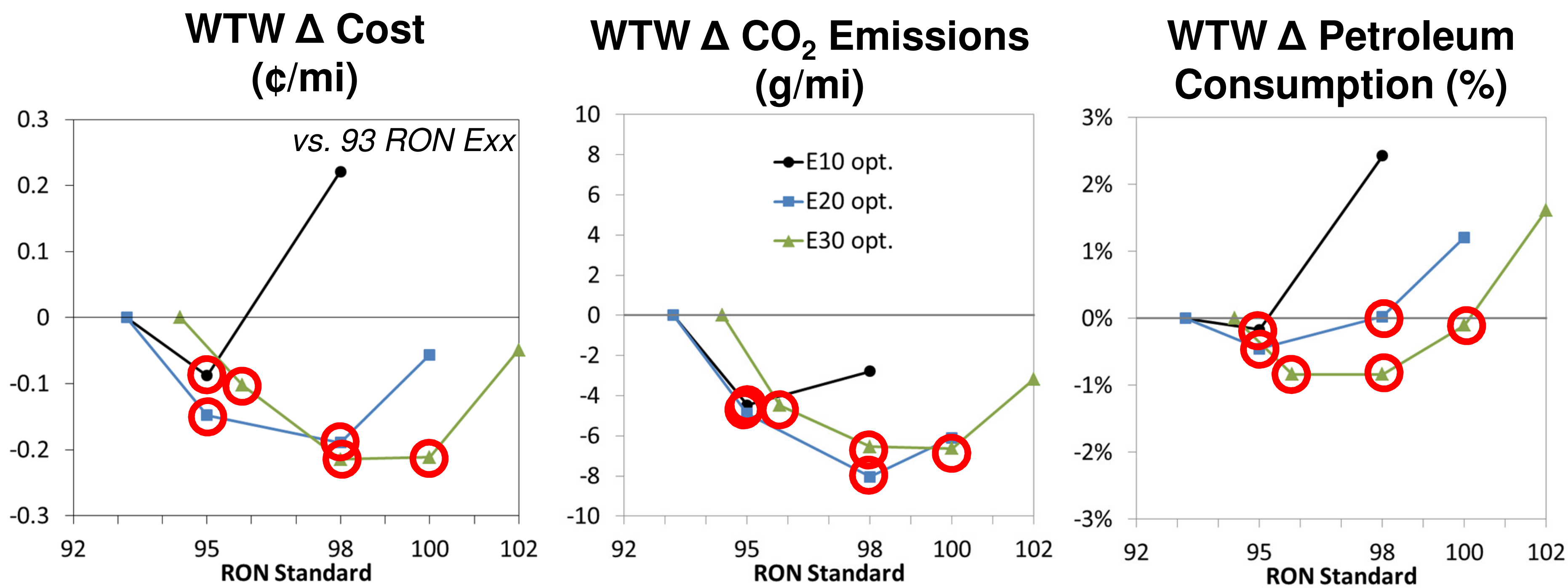
Δ Fuel Carbon Intensity (gCO_2/MJ)



 # Hirshfeld et al., ES&T, 2014.

Greatest TTW CO_2 emissions benefit for higher octane and higher ethanol blends in optimized engines (higher CR)

Well-To-Wheels Results

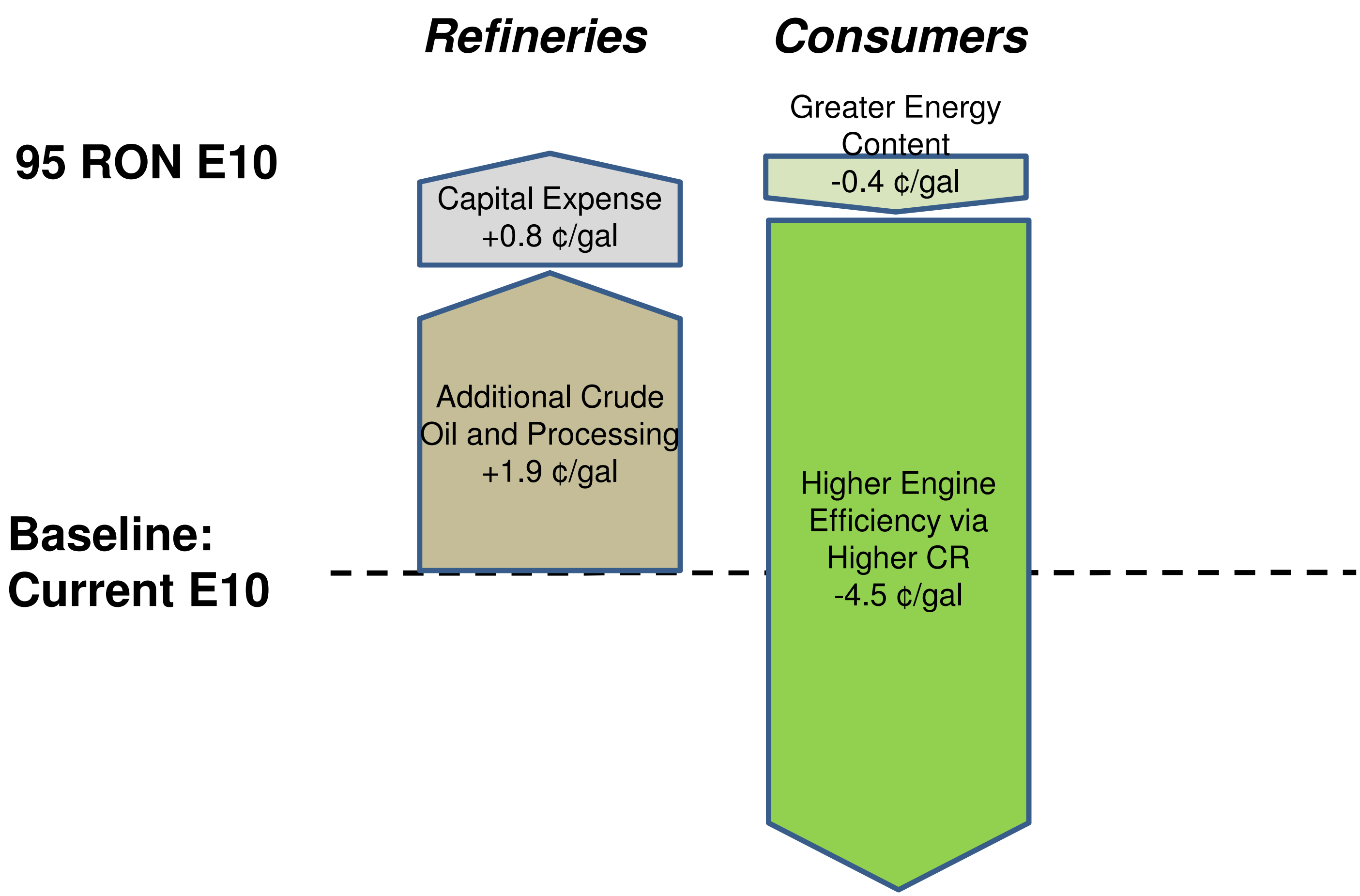


All results relative to 93-RON with respective ethanol content.

"Win-Win-Win" scenarios

Engine CR optimization enabled by higher octane ratings can yield reductions in net cost, CO_2 emissions, and petroleum consumption

WTW: Cost Breakdown Example



Net 2.3 ¢/gal savings

Fuel cost increase offset by consumer fuel savings in higher efficiency vehicles (higher CR) enabled by higher octane fuels

Conclusions

Higher octane gasoline provides an opportunity to increase light duty vehicle efficiency and reduce CO_2 emissions using the predominant fuel in the U.S. market.

Ethanol is one attractive fuel option to increase octane and reduce GHG footprint.

Higher octane gasoline can provide simultaneous reductions in WTW CO_2 emissions, crude oil use, and societal cost.