# QUANTIFYLING ETHANOL CARBON INTENSITY IN GASOLINE BLENDS

**Nigel N. Clark, Tammy Klein and David L. McKain, Jr.,**
**Transport Energy Strategies**
**&**
**Terrence Higgins**
**THiggins Energy Consulting**

**Coordinating Research Council**
**29th CRC Real World Emissions Workshop**
**Long Beach, CA**
**10-13 March 2019**

# Introduction

- Gasoline composition affects two separate Greenhouse Gas (GHG) measures
  - Carbon dioxide equivalent production at the tailpipe is regulated by the EPA
  - Total contribution of gasoline to the global GHG inventory is calculated as the product of gasoline consumed and its well-to-wheels (WTW) carbon intensity (CI)
- There are two different values for CI of a fuel
  - Tailpipe: Chemical CI is the ratio of actual carbon mass (as carbon dioxide mass) in the fuel to the net heating value of the fuel (g/MJ)
  - GHG Inventory: WTW CI includes fuel production and transportation, renewable components
- Most gasoline in the US contains ethanol, usually at 10% by volume (E10)
- Studies funded by the Urban Air Initiative (UAI) examined the quantitative tailpipe and WTW CI reductions offered by ethanol blending
- Small improvements in engine energy efficiency due to blending represent an additional adjustment (e.g. EPA Tier 2 / Tier 3 study)

# Chemical Carbon Intensity

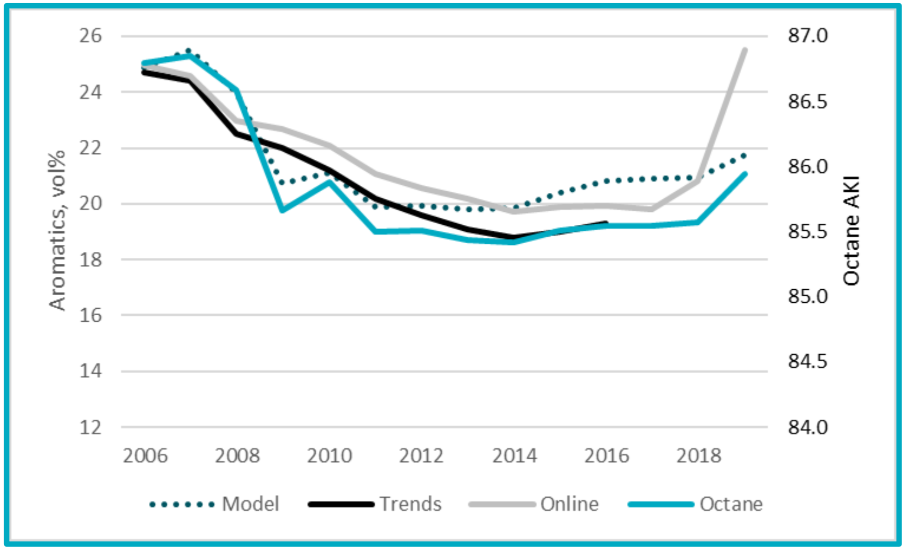
- Tank-to-Wheels (TTW) concept
- CI = (Grams $CO_2$)/LHV

- Ethanol + Blendstock for Oxygenate Blending (BOB) = Market Gasoline
- The BOB is a complex mixture of paraffins, isoparaffins, olefins, napthenes and aromatics
- Paraffins have high heating value and low carbon content, hence low CI
- Aromatics have low heating value and high carbon content, hence high CI
- Ethanol CI is slightly lower (71 g/MJ) than for a typical BOB or gasoline (about 72.5 g/MJ)

| PARAFFIN SPECIES | FORMULA | Grams $CO_2$/gram | LHV (MJ/kg) | Grams $CO_2$/MJ |
|---|---|---|---|---|
| Butane | C4H10 | 3.028 | 45.3 | 66.9 |
| Hexane | C6H14 | 3.064 | 44.7 | 68.6 |
| Octane | C8H18 | 3.082 | 44.4 | 69.5 |
| Decane | C10H22 | 3.093 | 44.2 | 70.0 |
| | | | | |
| ISO-PARAFFIN SPECIES | | | | |
| Iso-butane | C4H10 | 3.029 | 45.2 | 67.1 |
| 2,2,4 Trimethylpentane | C8H18 | 3.082 | 44.0 | 70.1 |
| 2,3,4 Trimethylpentane | C8H18 | 30.82 | 44.3 | 69.6 |
| 3-Ethylhexane | C8H18 | 3.082 | 44.3 | 69.6 |
| 3-Methyloctane | C9H20 | 3.088 | 44.5 | 69.4 |
| | | | | |
| AROMATIC SPECIES | | | | |
| Benzene | C6H6 | 30380 | 40.1 | 84.3 |
| ortho-Xylene | C8H10 | 3.316 | 40.8 | 81.3 |
| para-Xylene | C8H10 | 3.316 | 40.4 | 82.2 |
| Indane | C9H10 | 3.352 | 40.3 | 87.4 |
| Napthalene | C10H8 | 3.434 | 38.8 | 88.6 |
| | | | | |
| NAPTHENE SPECIES | | | | |
| Cyclopentane | C5H10 | 3.138 | 43.8 | 71.7 |
| Cyclohexane | C6H12 | 3.138 | 43.4 | 72.3 |
| 1,1-Dimethyl-cyclohexane | C8H16 | 3.138 | 43.2 | 72.6 |
| n-Butyl-cyclohexane | C10H20 | 3.138 | 43.9 | 75.2 |
| | | | | |
| OLEFIN SPECIES | | | | |
| Butene-2 | C4H8 | 3.138 | 44.7 | 70.2 |
| 2-Methyl-pentene-1 | C6H12 | 3.138 | 44.2 | 74.6 |
| Octene | C8H16 | 3.138 | 44.2 | 73.3 |
| 1,3-Pentadiene | C5H8 | 3.230 | 44.5 | 76.3 |
| | | | | |
| ALCOHOL SPECIES | | | | |
| Ethanol | C2H5OH | 1.953 | 26.9 | 71.0 |

# Ethanol – Aromatic Tradeoff

- Finished gasoline must meet octane requirement:
  AKI = (RON+MON)/2
- Ethanol has a high Blending Octane Number (BON), allowing adjustment of the BOB AKI
- Model considers EIA refinery operating and capacity data, gasoline demand, blend component properties, sulfur and benzene reductions and the EPA fuel trends report
- Ethanol increase is associated with a decrease in aromatics (10% increase implies 8.9% decrease)

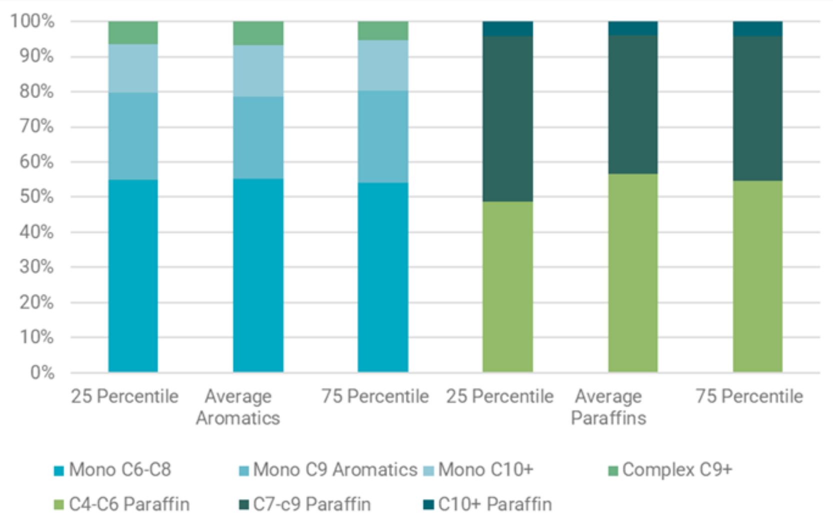



*Aromatic and Refinery Octane Trends (Model, EPA data) (Recent aromatic rise artifact due to dye shortage)*

| | Reduction in Aromatic Content |
|---|---|
| Model 2006-2013 Calculated, Extrapolated | 9.2% |
| Model Calculated E0-E10 | 9.0% |
| Actual EPA Trends Data Extrapolated[1] | 9.7% |
| Actual EPA Online Data Extrapolated[1] | 8.6% |
| EPA Tier 3 Modeling Extrapolated | 8.2% |
| **Average of Above** | **8.9%** |
| [1] Adjusted for changes in gasoline sulfur and benzene. | |

*Changes in aromatics in response to 10% ethanol addition*

# Modeled Market Fuel Composition




*Aromatic and Paraffin Species: Texas Survey Data*

- E10 market data available from 2017 Texas Summer Fuels Survey, providing base case
- Several Market Compositions modeled
  - Maintaining current refinery **prod**uction and increasing exports for ethanol change
  - Reducing refinery production for domestic **demand** & keep exports constant
  - **Splash** Blending with E10
  - Summer Regular, Winter Regular (low aromatic), Summer Premium (high aromatic) baselines
- CI and CI reduction versus projected E0 composition computed.

| | RON | Aromatics | Carbon | Energy | C Intensity | CO2 CI | CI Reduction |
|---|---|---|---|---|---|---|---|
| | | vol% | wt% | MBTU/# | #C/MMBTU | g/mg Joule | % vs E0 |
| E0 | 92.4 | 29.9 | 86.60 | 114.4 | 46.67 | 73.52 | |
| E10 w BOB | 93.0 | 21.7 | 82.34 | 109.9 | 46.01 | 72.48 | -1.41% |
| E15 w BOB & Prod | 93.3 | 17.9 | 80.14 | 107.4 | 45.63 | 71.89 | -2.23% |
| E15 w BOB Demand | 93.4 | 17.2 | 80.06 | 107.2 | 45.55 | 71.76 | -2.40% |
| E15 Splash w E10 BOB | 94.6 | 20.3 | 80.37 | 107.9 | 45.86 | 72.25 | -1.74% |
| E20 w BOB & Prod | 93.3 | 15.4 | 78.14 | 105.3 | 45.41 | 71.54 | -2.70% |
| E20 w BOB Demand | 93.4 | 14.0 | 77.98 | 105.0 | 45.25 | 71.29 | -3.04% |
| E20 Splash w E10 BOB | 96.0 | 19.2 | 78.49 | 106.0 | 45.76 | 72.09 | -1.95% |

*Ethanol, Aromatics and CI for summer regular scenarios*

# Tailpipe Blending CI

**Ethanol lowers CI in three ways**

1. Ethanol has lower CI than BOB or finished gasoline
2. Ethanol enables aromatic reduction, reducing CI of blend (highest contribution)
3. Ethanol blend fuel alters energy efficiency and $CO_2$ production of the vehicle engine (R-factor)

➢ *Way 3 is demonstrated by EPA Tier 2/ Tier 3 Certification Fuel report (1.31% lower CI -> 1.66% lower $CO_2$)*

**Viewing ethanol as the enabler for ways 1 and 2 assigns a reduced tailpipe *Blending* CI (BCI) to Ethanol**

*Example:* $1\ MJ\ x\ CI_{finished\ gasoline} =$
$0.069\ MJ\ x\ BCI_{ethanol} + 0.931\ MJ\ x\ CI_{E0}$

$$BCI_{ethanol} = \frac{1\ MJ\ x\ CI_{E10} - 0.931\ MJ\ x\ CI_{E0}}{0.069\ MJ}$$

$$= 58.9\ \frac{g\ CO_2}{MJ}$$

| | Ethanol | | | Petroleum | | | Total | Ethanol |
|---|---|---|---|---|---|---|---|---|
| | Energy (MJ) | TTW CI (g/MJ) | TTW CO2 (g/MJ) | Energy (MJ) | TTW CI (g/MJ) | TTW CO2 (g/MJ) | TTW CO2 (g) | BCI (g/MJ) |
| E0 w BOB | 0 | 71.0 | 0.0 | 1 | 73.5 | 73.5 | 73.5 | N/A |
| E10 w BOB & Prod | 0.069 | 71.0 | 4.9 | 0.931 | 72.6 | 67.6 | 72.5 | 58.9 |
| E15 w BOB & Prod | 0.106 | 71.0 | 7.5 | 0.894 | 72.0 | 64.4 | 71.9 | 58.3 |
| E20 w BOB & Prod | 0.144 | 71.0 | 10.2 | 0.856 | 71.7 | 61.4 | 71.6 | 60.3 |

*1 MJ Basis: E10, E15 & E20 Tailpipe BCI values are 17% lower than pure ethanol chemical CI*

# Well-to-Wheels (WTW) GHG Analysis

- WTW CI analysis differs from Tailpipe CI
- Petroleum gasoline is assigned its tank-to-wheels chemical CI (about 72.5 g/MJ), adjusted upward for production, refining and transportation impacts (typical total WTW  93 g/MJ)
- Ethanol from corn (US) is deemed renewable and assigned zero chemical CI, but is assigned CI for agricultural energy, fertilizer, production, transportation and land-use change (LUC)
  - *Efficiency of agriculture is rising, which lowers Ethanol CI (ICF, Lee et al.)*
  - *Ethanol is assigned CI credits for useful byproducts (e.g. corn oil)*
  - *LUC CI prediction varies substantially between studies*
- Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model has a 20+ year history. Wang et al. (2021): 43,800 GREET users globally in 2020
- Ethanol WTW CI 43.4% lower than for gasoline (GREET); 38% lower (CARB); 39.7% & 44.3% lower (ICF/USDA); 46% lower (Scully et al.)
- Lesser reduction for older studies and high LUC components

# Applying BCI to WTW CI

- Published models are for pure or adulterated ethanol
- Gasoline blending advantage of reduced aromatics not considered: BCI is lower than CI.
- Using GREET Ethanol CI (52.4 g/MJ), BCI for E10 & E15 is 40 g/MJ; BCI for E20 is 42g/MJ
- Equivalently, WTW CI for E15 blend is 9.4% below E0

| Blend (1MJ) | Ethanol Energy (MJ) | Ethanol WTW CI (g/MJ) | Ethanol WTW CO2 (g) | Petroleum Energy (MJ) | Petroleum WTW CI (g/MJ) | Petroleum WTW CO2 (g) | Total WTW CO2 (g) | Ethanol BCI (g/MJ) |
|---|---|---|---|---|---|---|---|---|
| E0 w BOB | 0 | N/A | 0.00 | 1 | 92.6 | 92.6 | 92.60 | N/A |
| E10 w BOB & Prod | 0.069 | 52.4 | 3.62 | 0.931 | 91.7 | 85.37 | 88.99 | 40.26 |
| E15 w BOB & Prod | 0.106 | 52.4 | 5.55 | 0.894 | 91.1 | 81.44 | 87.00 | 39.75 |
| E20 w BOB & Prod | 0.144 | 52.4 | 7.55 | 0.856 | 90.8 | 77.72 | 85.27 | 41.70 |

*92.6 g/MJ is gasoline CI from GREET*

# Comparison & Conclusions

## COMPARATIVE IMPACT

- A gasoline vehicle emits approximately twice the $CO_2$ equivalent of a BEV powered by a natural gas power plant
  - Gas production & transmission
  - Upstream methane emissions
  - Powerplant efficiency
  - Transmission efficiency
  - Charging efficiency
  - Cabin heat
- 1 MJ of blended ethanol displacing 1MJ of gasoline has a similar GHG reduction
  - Aromatic decrease reduces CI
  - Ethanol itself has low WTW CI
- **BCI effectiveness of ethanol encourages use alongside BEV & sustainable grid adoption**
  - Immediate benefit with existing fleet vehicles

## CONCLUSIONS

- Ethanol enables reduction of aromatics in gasoline while maintaining octane number
- Tailpipe $CO_2$ reduced by 2.2% for E15 vs E0
- Assigning benefit to ethanol supports BCI concept
- Ethanol BCI 17% lower than chemical CI
- WTW CI for ethanol and petroleum includes multiple upstream components
- On GREET basis, WTW BCI for ethanol (e.g. E10, E15) is 40 g/MJ compared to 92.6 for E0 gasoline
- **Ethanol has far higher GHG benefits in blends than as a pure fuel**

# Two detailed reports

transportenergy strategies

## Quantifying Ethanol CI Benefits in Gasoline Composition

https://www.transportenergystrategies.com/wp-content/uploads/sites/7/2021/10/Tasks2-4_FIN_Oct2021.pdf

transportenergy strategies

## Well-to-Wheels Carbon Intensity for Ethanol Blended Fuels

https://www.transportenergystrategies.com/wp-content/uploads/sites/7/2021/09/Well-to-Wheels_CI_FIN.pdf


REFERENCES (see reports for additional references)

- EPA 2018 Environmental Protection Agency Tier 3 Certification Fuel Impacts Test Program EPA-420-R-18-004
- California Air Resources Board (CARB). 2021a. Low Carbon Fuel Standard Program. “Substitute Pathways and Default Blend Levels for LCFS Reporting for Specific Fuel Transaction Types.” Accessed August 2021
- Wang, M., Lee, U., Kwon, H. and Xu, H., 2021. “Life-Cycle Greenhouse Gas Emission Reductions of Ethanol with the GREET Model,” National Ethanol Conference, February 17, 2021
- Lee, U., Kwon, H., Wu, M., and Wang, M. 2021. “Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: Implications for greenhouse gas emission reductions,” DOI: 10.1002/bbb.2225
- Rosenfeld, J., Lewandrowski, J., Hendrickson, T., Jaglo, K., Moffroid, K., and Pape, D. 2018. “A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol.” ICF Report for USDA: Contract No. AG-3142-D-17-0161. 2018
- Scully, M., Norris, G., Alarcon, T. and MacIntosh, D., 2021.” Carbon intensity of corn ethanol in the United States: state of the science,” Environ. Res. Lett. 16 (2021) 043001 DOI: 10.1088/1748-9326/abde08