October 5, 2017

Attention: Docket ID No. EPA–HQ–OAR–2015–0827
Docket ID No. NHTSA–2016–0068

U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW
Washington, DC 20460

National Highway Traffic Safety Administration
1200 New Jersey Avenue SE
Washington, DC 20590

RE: Comments of the Renewable Fuels Association in Response to the Request for Comment on Reconsideration of the Final Determination of the Mid-Term Evaluation of Greenhouse Gas Emission Standards for Model Year 2022-2025 Light-Duty Vehicles, 82 Fed. Reg. 39,551 (August 21, 2017)

The Renewable Fuels Association ("RFA") appreciates the opportunity to provide comments relevant to the Administrator's reconsideration of the January 2017 Final Determination of the Mid-term Evaluation of greenhouse gas emissions ("GHG") standards for model year 2022–2025 light-duty vehicles. As the leading trade association representing America's ethanol industry, RFA's mission is to advance the development, production, and use of fuel ethanol by strengthening America's ethanol industry and raising awareness about the benefits of renewable fuels.

RFA particularly welcomed the Request for Comment's focus on the "potential for high-octane blends."[1] As expressed in comments previously submitted by RFA to the Environmental Protection Agency ("EPA") and National Highway Traffic Safety Administration ("NHTSA") (Attachments A and B), we were disappointed that the January 2017 Final Determination and the 2016 Technical Assessment Report ("TAR") largely ignored the role of octane, "the single most important property of gasoline" in determining engine design.[2] Because the fuels Americans put in their engines have a significant impact on fuel economy and GHG emissions, RFA has encouraged the EPA and NHTSA throughout this rulemaking to evaluate *both engines and fuels as integrated systems* when assessing the efficacy of model year 2022-2025 fuel economy and GHG standards.

[1] 82 Fed. Reg. 39551, 39553 (Aug. 21, 2017).
[2] Julian Soell and R. Thomas Brunner, Mercedes-Benz, Comments on Proposed Tier 3 Rule, EPAHQ-OAR-2011-0135-4676, at 3 (June 28, 2013).

These written comments, which supplement RFA's oral comments from the September 6, 2017 public hearing on this matter, focus on: 1) the importance of considering engines and fuels as integrated systems for the purposes of the 2022-2025 CAFE/GHG standards; 2) the fuel economy and emissions benefits of high-octane low carbon (HOLC) fuels; and 3) how EPA can utilize existing statutory authorities to promote higher octane fuels.

I. EPA's Final Determination should treat engines and fuels as integrated systems because fuel properties can have significant effects on fuel economy and emissions

By itself, the internal combustion (IC) engine does nothing to propel a light duty vehicle or generate GHG emissions. It is only when a liquid fuel is introduced into the engine that the technology works to deliver the service of mobility. In this way, IC engines and liquid fuels combine to form a highly integrated system in which one component is useless without the other. Indeed, the IC engine's efficiency and emissions can be greatly affected by the characteristics of the liquid fuel used in the engine. Unfortunately, in assessing the technologies potentially used to meet MY2022-2025 CAFE and GHG standards, the Final Determination and TAR focused almost exclusively on the engine component of this system and give no consideration to the effect of various fuel properties on fuel economy and emissions. This is a significant shortcoming of the Final Determination process to date.

a. EPA and NHTSA should follow the example of DOE, whose Co-Optima program appropriately recognizes the symbiotic relationship between fuels and engines

Recognizing that fuels and engines must be developed in concert to maximize efficiency and emissions reductions, the U.S. Department of Energy has launched an initiative to focus on "Co-optimization of Fuels and Engines for Tomorrow's Energy Efficient Vehicles." The initiative, known simply as "Co-optima," endeavors to "…simultaneously tackle fuel and engine innovation to co-optimize performance of both elements and provide dramatic and rapid cuts in fuel use and emissions."[3] Co-optima has two major research tracks, the first of which is "…improving near-term efficiency of spark-ignition engines through the identification of fuel properties and design parameters of existing base engines that maximize performance."[4] Importantly, this track includes identifying "candidate fuels" for use in co-optimized engines to achieve peak performance, energy efficiency and emissions reductions. The "market introduction target" for co-optimized fuels and IC engines under this research track is 2025.

A recent summary of DOE research conducted as part of the Co-optima program demonstrates that significant additional improvement in fuel economy and GHG emissions reduction can occur when advanced IC engines are paired with HOLC fuels.[5] Automakers have also advocated

[3] U.S. Department of Energy. *Co-Optimization of Fuels & Engines for Tomorrow's Energy-Efficient Vehicles.* Available at: http://www.nrel.gov/docs/fy16osti/66146.pdf
[4] *Id*.
[5] Oak Ridge National Laboratory. July 2016. *Summary of High-Octane, Mid-Level Ethanol Blends Study*. ORNL/TM-2016/42

for a coordinated approach to the development and regulation of engines and fuels. According to Dan Nicholson, vice president of global propulsion systems at GM, "Fuels and engines must be designed as a total system. It makes absolutely no sense to have fuel out of the mix."[6]

EPA and NHTSA tangentially acknowledged the importance of the Co-optima initiative in the TAR, stating that the agencies "…will continue to closely follow the Co-Optima program and provide input to DOE, including through EPA's technical representative on the Co-Optima External Advisory Board, as this program has the potential to provide meaningful data and ideas for GHG and fuel consumption reductions in the light-duty vehicle fleet for 2026 and beyond." However, this statement is the closest the TAR got to examining future engine technologies and fuels in a holistic, systems-based manner.

II. Pairing advanced internal combustion engine technologies with high octane low carbon (HOLC) fuels would result in greater fuel economy and emissions benefits than considered by EPA and NHTSA in the TAR and Final Determination.

As underscored elsewhere in these comments, EPA's TAR and January 2017 Final Determination examined only the potential fuel economy and emissions improvements expected to result from adoption of various advanced IC engine technologies. The TAR does not consider the ability of HOLC fuels to multiply these fuel economy and emissions improvements. In essence, the TAR assumes the status quo for liquid fuels, meaning significant additional fuel economy improvements and emissions reductions are overlooked.

According to a review of the TAR by automotive engineering firm Ricardo (included in Attachment A), "…many of the technologies that are discussed in the Draft TAR, including the ones with the highest expected penetration rates, could produce *greater* GHG and fuel economy benefits if paired with fuels offering higher octane ratings than contemplated by EPA and NHTSA for the agencies' modeling exercises."

Numerous studies by the automotive industry, DOE, and academia have examined the efficiency gains and emissions reductions that can be achieved when HOLC fuels is used in an IC engine with HCR, turbocharging, and other advanced technologies discussed in the TAR. These studies have repeatedly shown that a high octane fuels (98-100 RON) used in HCR engines improves efficiency and reduces emissions by 4-10%, depending on drive cycle and other factors. Studies using a high octane mid-level ethanol blend also demonstrate that fuel economy and vehicle range using HOLC blends like E25 and E30 is equivalent or superior to performance using E10, even though the E25 and E30 blends have lower energy density. A new literature review by Ricardo summarizes the growing body of research that demonstrates the efficiency and emissions benefits of HOLC fuels (Attachment C).

a. Ethanol's unique properties make it an attractive candidate for boosting octane in future HOLC fuel blends

[6] Society of Automotive Engineers. Aug. 3, 2016. *GM, Honda execs agree: Higher octane gas needed to optimize ICE efficiency.* http://articles.sae.org/14940/

Certain chemical properties, such as "sensitivity" and heat of vaporization, make some octane boosters more attractive than others. As researchers have examined different methods of boosting gasoline octane ratings, one option—increased levels of ethanol—has stood out as the most efficient and economical pathway.

Not only does ethanol offer extremely high octane (109 RON, 91 MON), it also features high sensitivity and high heat of vaporization. These are attractive properties that, when considered along with ethanol's lower "lifecycle" carbon intensity and lower cost relative to other octane options, make ethanol the clear choice for future HOLC fuels. The importance of octane sensitivity and heat of vaporization are discussed in great detail in the Ricardo review of the TAR. Ricardo states that these benefits are important considerations for "…DI engines especially, both NA and turbocharged, which are expected to comprise the majority of future engines for both conventional and hybrid vehicles."

In addition to the tailpipe CO_2 reductions observed in several of the studies cited in these comments, ethanol-based HOLC fuels also offer important lifecycle GHG emissions benefits. That is, the total "well-to-wheels" (WTW) emissions associated with producing and using ethanol are significantly lower per unit of energy delivered than the emissions resulting from petroleum production and use. The latest analysis conducted by DOE's Argonne National Laboratory found that today's corn ethanol reduces GHG emissions by an average of 34-44% compared to petroleum, while emerging cellulosic ethanol technologies offer GHG reductions of 88-108%.[7] Similarly, a recent analysis commissioned by the U.S. Department of Agriculture found that 2014-era corn ethanol offered a 43% GHG reduction, on average, compared to gasoline.[8] These benefits are compounded when the ethanol is used in a HOLC fuel that achieves greater fuel economy and vehicle range (i.e., more miles with less energy) than today's marketplace fuels.

In a recent study, Argonne National Laboratory examined the WTW GHG emissions impacts of HOLC fuels (100 RON) containing 25% and 40% ethanol.[9] The analysis found that the inherent efficiencies resulting from using a high octane fuel in a HCR engine alone resulted in a 4-8% reduction in GHG emissions per mile compared to baseline E10 gasoline vehicles. Additional GHG reductions of 4-9% were realized as a result of corn ethanol's lower lifecycle emissions upstream, meaning total GHG emissions per mile were 8% and 17% lower for E25 and E40, respectively, compared to baseline E10. Meanwhile, E25 and E40 HOLC blends made with cellulosic ethanol were shown to reduce total WTW GHG emissions by 16-31% per mile compared to E10. While high octane fuels using petroleum-derived octane sources may provide similar tailpipe CO_2 reductions as

[7] Wang, M.; Han, J.; Dunn, J. B.; Cai, H.; Elgowainy, A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environ. Res. Lett. 2012, 7, 1−13, DOI: 10.1088/1748-9326/7/4/045905

[8] Flugge, M., J. Lewandrowski, J. Rosenfeld, C. Boland, T. Hendrickson, K. Jaglo, S. Kolansky, K. Moffroid, M. Riley-Gilbert, and D. Pape, 2017. A Life-Cycle Analysis of the Greenhouse Gas Emissions of Corn-Based Ethanol. Report prepared by ICF under USDA Contract No. AG-3142-D-16-0243. January 30, 2017.

[9] Oak Ridge National Laboratory. July 2016. *Summary of High-Octane, Mid-Level Ethanol Blends Study*. ORNL/TM-2016/42

ethanol-based HOLC fuels, they clearly do not offer the additional GHG reductions associated with ethanol's full WTW lifecycle.

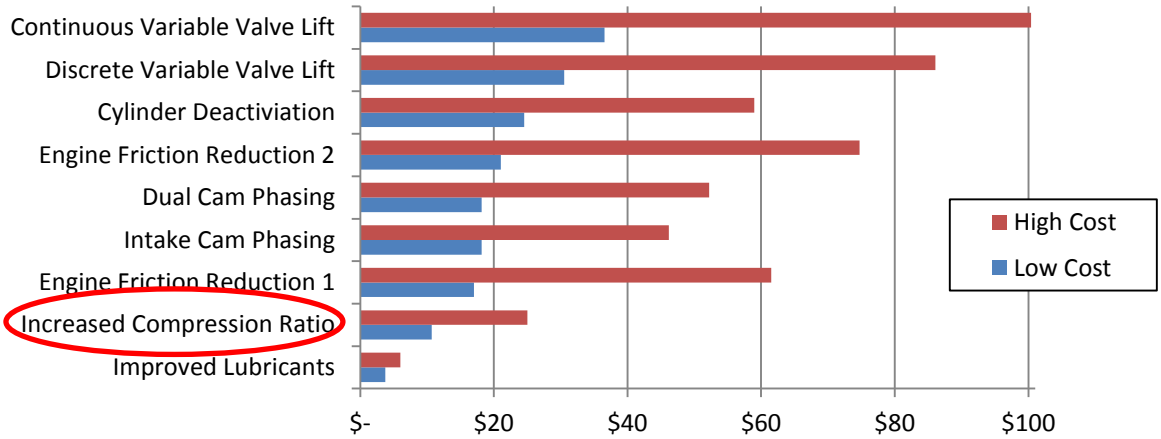
Additional studies show that using ethanol as the source of octane in future high octane fuels has the potential to significantly decrease petroleum refinery GHG emissions by reducing the energy intensity of the refining process.[10]

b. Use of an ethanol-based HOLC in optimized IC engines would be the lowest cost means of achieving compliance with CAFE and GHG standards for MY2022-2025 and beyond

A central objective of the TAR that informed the Final Determination is to estimate the potential costs associated with various technology pathways for achieving the MY2022-2025 CAFE and GHG standards. Again, however, the TAR tends to examine only the expected costs associated with various engine and vehicle technologies, with little or no consideration given to the associated fuel costs over the vehicle's life.

When only the costs of various engine technologies are considered, HCR stands out as one of the most cost-effective means available for increasing engine efficiency (Figure 1).

Figure 1. Cost per Percentage Point Increase in Engine Efficiency



Based on NRC (June 2015); Draft TAR (July 2016); AIR, Inc. (Sep. 2016)

The National Research Council estimates that the cost to the automaker to introduce higher compression ratio for use with "higher octane regular fuel" is likely $75-150 per vehicle.[11] However, analysis by Air Improvement Resource, Inc. suggests "…costs of increased compression ratio would be near zero, especially if it were accomplished during normal engine re-design cycles." Similarly,

[10] See "Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content", DS Hirshfeld, JA Kolb, JE Anderson, W Studzinski, and J Frusti. (2014) dx.doi.org/10.1021/es5021668 | Environ. Sci. Technol. 2014, 48, 11064-11071; and "Petroleum refinery greenhouse gas emission variation related to higher ethanol blends at different gasoline octane rating and pool volume levels", V Kwasniewski, J Blieszner, and R Nelson, DOI: 10.1002/bbb.1612; Biofuels, Bioprod. Bioref (2015)

[11] NRC. June 2015. TABLE S.2 NRC Committee's Estimated 2025 MY Direct Manufacturing Costs of Technologies

Ricardo notes that "Since the costs to an OEM for increasing compression ratio are minimal for a new engine design, it is clear that implementing a high octane mid-level ethanol fuel standard would be the lowest cost technology and have even greater benefits in real world driving."

Still, the engine technology cost is only one-half of the equation when total vehicle purchase and operation costs are considered; fuel costs must also be considered. To examine the total cost of high compression ratio engines using a HOLC fuel (98 RON E25) as a technology pathway for compliance with 2022-2025 CAFE and GHG standards, Air Improvement Resource, Inc. (AIR) conducted a study using the same OMEGA model used by EPA and NHTSA for the TAR. The AIR study found that this pathway can substantially reduce the cost of compliance with the standards, concluding that "With higher compression ratio engines included, total costs of the 2025 model year standards are reduced from $23.4 billion to $16.8 billion. …This analysis has shown that if a high octane mid-level blend ethanol fuel such as 98-RON E25 were an option for model year 2022-2025 vehicles meeting EPA's GHG standards, overall program costs would be significantly reduced."

c. Increasing octane should not come at the expense of air quality, carbon emissions, or human health

The potential for significant environmental, economic, and public health benefits from introducing higher octane fuels is obvious. However, the transition to higher octane fuels must be accompanied by requirements that octane sources improve air quality, reduce carbon emissions, and protect public health. Without such protections, there is the potential that increasing gasoline octane could result in unnecessary backsliding on criteria air pollutants, air toxics, and other harmful emissions linked to certain high-octane hydrocarbons. When it comes to air quality and human health, not all octane sources are created equal. Ethanol reduces criteria pollutants, and is the only source of octane that is truly renewable and results in a significant reduction in carbon. But much of the octane contribution in today's gasoline comes from petroleum-derived aromatic hydrocarbons such as benzene, toluene, and the C8 aromatics like xylene. Those sources of octane are far from benign.

The health impacts of aromatic hydrocarbons are well known. A 2015 study published in the *American Journal of Epidemiology* linked benzene found in traffic emissions to childhood leukemia. A 2012 study published by the University of California ties the risk of autism to toxics found in traffic pollution. And a 2015 study published in the *Journal of Environmental Health Perspectives* links microscopic toxic particles in car exhaust to heart disease. Aromatic hydrocarbons compose 20-50% of the non-methane hydrocarbons in urban air and are considered to be one of the major precursors to urban secondary organic aerosols (SOA). SOA is a form of fine particulate matter pollution (PM2.5), which is widely viewed as the most lethal air pollutant in the U.S. today. Moreover, new evidence is confirming that particulate matter from gasoline exhaust is a major source of black carbon, which is thought to be a significant contributor to climate change.

To date, EPA has been relatively quiet on the growing health and environmental threat posed by increased aromatics in gasoline. Because increasingly stringent fuel economy and GHG standards will likely result in increased use of higher octane fuels, the EPA must take into consideration the

ancillary health and climate impacts of the various octane sources, and assure that no backsliding can occur.

III. Automotive engineers and executives, Department of Energy researchers, the National Research Council, and academia all are calling for HOLC fuels to increase fuel economy and decrease GHG emissions

Over the past several years, a growing chorus of automotive engineers and executives, government scientists, expert panels, and university researchers has called for the introduction of HOLC fuels. These experts have clearly demonstrated that HOLC fuels would enable HCR engines and other advanced IC engine technologies, which in turn would improve engine efficiency and reduce emissions. Below is a partial list of statements from these experts regarding the need for HOLC fuels.

- "Higher octane is necessary for better engine efficiency. It is a proven low-cost enabler to lower CO2; 100 RON fuel is the right fuel for the 2020-2025 timeframe."*—Dan Nicholson, vice president of global propulsion systems, GM*[12]
- "100 RON has been on the table for a long time. The only way we will ever get there is to continue to push and work in a collaborative way." – *Tony Ockelford, director of product and business strategy for powertrain operations, Ford Motor Company*[13]
- "We need to find a new equilibrium. Whether it is 98 or 100 (RON) octane, we need something at that level*."— Bob Lee, head of powertrain coordination, Fiat Chrysler*[14]
- "…it appears that substantial societal benefits may be associated with capitalizing on the inherent high octane rating of ethanol in future higher octane number ethanol-gasoline blends." – *Ford Motor Company*[15]
- "…a mid-level ethanol-gasoline blend (greater than E20 and less than E40) appears to be attractive as a long-term future fuel for automotive engines in the U.S." – *AVL Powertrain Engineering and Ford Motor Company*[16]
- "There has been a big push in the industry for higher octane ratings…and it is proven that you can gain several percentage points in improvement of fuel economy if you have higher octane rating fuel available." – *Dean Tomazic, executive vice president and chief technology officer, FEV North America*[17]

---

[12] Truett, Richard. Automotive News. April 13, 2016. *Powertrain executives press for higher octane gasoline to help meet mpg, CO2 rules.*
[13] *Id*.
[14] *Id*.
[15] J.E. Anderson et al. July 2012. *High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States*. Fuel, Volume 97: Pages 585–594.
[16] Stein, R., Anderson, J., and Wallington, T., "An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions," *SAE Int. J. Engines* 6(1):470-487, 2013, doi:10.4271/2013-01-1635.
[17] Detroit Public Television. Aug. 21, 2016. *Autoline with John McElroy*. Episode #2026 ("Deep Freeze for the ICE?")

- "One of the advantages without costing more on the vehicle side is to look at upping the minimum octane rating on the fuel and allowing OEMs to optimize compression ratio in engines, which would give us an efficiency benefit without actually adding cost to the whole system. …the addition of ethanol blends would be a good improvement to actually drive efficiency." – *David McShane, vice president of business development, Ricardo, Inc.*[18]

- "If we could optimize engines only to operate on premium fuel, then life would be a lot easier for us and we'd be able to see much more of a benefit in terms of efficiency. …if ethanol was widely available then our life as developers of gasoline engines would become easier." – *Paul Whitaker, powertrain & technical director, AVL Powertrain Engineering*[19]

- "(High octane fuels), specifically mid-level ethanol blends (E25-E40), could offer significant benefits for the United States. These benefits include an improvement in vehicle fuel efficiency in vehicles designed and dedicated to use the increased octane." – *Oak Ridge National Laboratory, Argonne National Laboratory, and National Renewable Energy Laboratory*[20]

- "Improvements to engine efficiency made possible with ethanol fuels may be a synergistic approach to simultaneous compliance with CAFE and RFS II. This presents a unique and infrequent opportunity to dramatically alter internal combustion engine operation by improving fuel properties." – *Oak Ridge National Laboratory*[21]

- "Several technologies beyond those considered by EPA and NHTSA might provide additional fuel consumption reductions for spark ignition engines or provide alternative approaches at possibly lower costs for achieving reductions in fuel consumption by 2025. These technologies include…higher compression ratio with higher octane regular grade gasoline…" – *National Research Council*[22]

- "[T]ransitioning the fleet to higher-octane gasoline would result in significant economic and environmental benefits through reduced gasoline consumption." – *Massachusetts Institute of Technology*[23]

IV. EPA has the authority—and the responsibility—to regulate gasoline octane levels.

EPA retains broad authority in Section 211(c) of the Clean Air Act to regulate octane content in gasoline if EPA's emissions standards cannot be achieved without increasing octane levels or if such an increase would significantly lower the costs of meeting the standards. As explained below,

---

[18] *Id.*
[19] *Id.*
[20] Oak Ridge National Laboratory. July 2016. *Summary of High-Octane, Mid-Level Ethanol Blends Study*. ORNL/TM-2016/42.
[21] Derek A. Splitter and James P. Szybist (2014) "Experimental Investigation of Spark-Ignited Combustion with High-Octane Biofuels and EGR. 2. Fuel and EGR Effects on Knock-Limited Load and Speed" *Energy & Fuels*.
[22] NRC. June 2015, at 2-84.
[23] R.L. Speth et al. Economic and environmental benefits of higher-octane gasoline. *Environ Sci Technol.* 2014 Jun 17;48(12):6561-8. doi: 10.1021/es405557p

the evidence before the agency supports such a conclusion. Alternatively, 211(f) can be used to increase octane levels in gasoline by facilitating the commercialization of mid-level ethanol blends.

a. EPA's Existing Authority to Regulate Octane Levels

i. *Clean Air Act Section 211(c) Provides Broad Authority for EPA to Promote High Octane Fuels*

Although EPA has not regulated gasoline octane directly, it has the authority to do so under section 211(c) of the Clean Air Act ("CAA"). That provision affords EPA broad authority to regulate any aspect of a fuel that affects vehicle emissions.[24] EPA has used this authority to regulate the composition of gasoline by restricting levels of lead, sulfur, and other additives. [25] Since octane levels impact emissions, EPA could use section 211(c) to control octane as well. Specifically, upon satisfying certain specified criteria discussed below, EPA could "control or prohibit the manufacture, introduction into commerce, offering for sale, or sale of" gasoline below a certain octane level.[26]

In order to invoke its authority under Section 211(c)(1)(A), EPA must demonstrate that the "fuel or fuel additive, or any emission product [thereof]… causes, or contributes, to air pollution…that may reasonably be anticipated to endanger public health or welfare."[27] If EPA were to promulgate regulations under this paragraph, it must consider "all relevant medical and scientific evidence," including "other technically or economically feasible means of achieving emissions standards" established under CAA section 202.[28] Although this language has been interpreted to mean that EPA must make a "good faith consideration of motor vehicle standards before imposition of fuel controls,"[29] EPA "retains full discretion in deciding whether to adopt either fuel or vehicle controls, or both."[30]

As explained further below, EPA can regulate octane under Section 211(c)(1)(A).[31]

---

[24] *See* S. Rep. No. 91-1196 (stating that "[a]t one time the Committee [on Public Works of the Senate] considered language that would give the Secretary only authority to 'prohibit' a fuel's introduction into commerce. After evaluation, the Committee decided that such authority should also be extended to the 'control' of a fuel's introduction into commerce. This authority to 'control' the use of a fuel is intended to give the Secretary greater flexibility, than the authority to 'prohibit'"); *see also* 61 Fed. Reg. 35310, 35313 (July 5, 1996) ("Section 211(c)(1) provides EPA broad authority to regulate the introduction into commerce, production, distribution, and sale of fuels and fuel additives to protect the public health and welfare.").

[25] *See e.g., Amoco Oil Co. v. EPA*, 501 F.2d 722, 743-744 (D.C. Cir. 1974) (upholding conditions on sale of leaded gasoline); U.S. EPA, "EPA's Regulatory Authority to Address Octane" at 4 (May 5, 2015).

[26] *See* 42 U.S.C. §7545(c)(1).

[27] 42 U.S.C. §7545(c)(1)(A).

[28] *Id*. §7545(c)(2)(A).

[29] 61 Fed. Reg. at 35313-35314 (citing *Ethyl Corp. v. EPA*, 541 F.2d 1, 32 n. 66 (D.C. Cir. 1976).

[30] *Id*. at 35314.

[31] Alternatively, EPA could utilize its authority to regulate octane under section 211(c)(1)(B) by showing that emission products associated with lower octane fuels "impair to a significant degree the performance of any emission control device or system." 42 U.S.C. §7545(c)(1)(B). The Agency's previous regulations under 211(c)(1)(B) restricting lead and sulfur were tied to the impairment of catalytic emission controls from emission products containing these elements. The same statutory authority would apply to octane – it would allow regulatory control over octane because low octane fuels impact engine compression ratios and impair the reduction in emissions that high compression systems would provide. If EPA were to choose this option, it must consider

b. EPA Can Regulate Octane Under Section 211(c)(1)(A) Because Low Octane Gasoline Contributes to Air Pollution and Increases the Cost to Comply with Vehicle Emissions Standards

Low octane gasoline (i.e., 87 AKI "regular" grade) has resulted in the widespread use of lower compression engines, which have higher carbon dioxide and other emissions than high compression engines using high octane fuel.[32] According to EPA, carbon dioxide emissions are a form of air pollution that endangers public health and welfare.[33] EPA has also determined that emissions from gasoline use cause or contribute to harmful air pollution.[34] EPA can therefore demonstrate that low octane gasoline contributes to air pollution that endangers public welfare. Although EPA previously found that vehicle manufacturers would be able to meet 2022-2025 GHG standards through the use of existing low octane fuels, studies previously submitted by RFA and others show that higher octane fuels would allow for greater emission reductions at lower cost than can be achieved by changing only engines.[35]

Use of higher octane, E20-E30 blends would provide significant carbon dioxide emissions reduction and several billion dollars of net savings each year.[36] Increasing the compression ratio of the engine not only increases fuel economy, but it also allows for engine downsizing, which further increase fuel economy. Studies suggest that legacy flex-fuel vehicles can benefit (e.g., faster acceleration) from high octane fuels as well.[37] With regard to economic feasibility, according to comments from the Alliance of Automobile Manufacturers, "implementation of higher octane rated

---

"available scientific and economic data, including a cost benefit analysis comparing emission control devices or systems which are or will be in general use and require the proposed control or prohibition with emission control devices or systems which are or will be in general use and do not require the proposed control or prohibition." *Id*. §7545(c)(2)(B).

[32] *See e.g*., Han et al., *Well-to-Wheels Greenhouse Gas Emissions with Various Market Shares and Ethanol Levels*, ANL-ESD-10-15, 64 (2015) (finding E25 blend with 100 RON could reduce lifecycle GHG emissions by 10 percent); M. Matti Maricq, et al., *The Impact of Ethanol Fuel Blends on PM Emissions from a Light-Duty GDI Vehicle*, 46 Aerosol Sci. & Tech. 576, 580 (2011) (finding that PM emissions are almost halved when the ethanol content of fuel is increased from 0% to 32% in a turbocharged GDI engine); John M. Storey et al., *Ethanol Blend Effects On Direct Injection Spark-Ignition Gasoline Vehicle Particulate Matter Emissions*, 3 SAE Int. J. Fuels Lubr. 650, 653 (2010) (finding 30 percent reduction in particulate matter emissions when using E20 compared to E0).

[33] Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act, 74 Fed. Reg. 66496 (Dec. 15, 2009).

[34] *See* 61 Fed. Reg. at 35313 (citing 58 Fed. Reg. 64213, 64215 (Dec. 6, 1993)) (regulating gasoline and gasoline detergent additives).

[35] Renewable Fuels Association, Comments of the Renewable Fuels Association (RFA) in response to Notice of Availability of Midterm Evaluation Draft Technical Assessment Report for Model Year 2022–2025 Light Duty Vehicle GHG Emissions and CAFE Standards, at 10 (Sept. 26, 2016) ("With higher compression ratio engines included, total costs of the 2025 model year standards are reduced from $23.4 billion to $16.8 billion. …This analysis has shown that if a high octane mid-level blend ethanol fuel such as 98-RON E25 were an option for model year 2022-2025 vehicles meeting EPA's GHG standards, overall program costs would be significantly reduced."); Oak Ridge Nat'l Laboratory, Summary of High-Octane, Mid-Level Ethanol Blends Study, at 16 (July 2016) (high-octane mid-level ethanol blends increase fuel efficiency in new vehicles by 5-10 percent).

[36] *See* Raymond Speth et al., Massachusetts Institute of Technology, "Potential Environmental and Economic Benefits of Higher-Octane Gasoline," CRC Workshop, Argonne National Laboratory at 14 (Oct. 28, 2015).

[37] Theiss, T., et al., U.S. DOE-Oak Ridge National Laboratory, National Renewable Energy Laboratory, and Argonne National Laboratory, "Summary of High-Octane Mid-Level Ethanol Blends Study" at 7, 16 (July 2016).

gasoline in the marketplace could be a cost-effective means of immediately improving fuel economy across a substantial portion of the existing light-duty vehicle fleet."[38] Although cost would arguably be a relevant factor for EPA to consider, EPA can adopt fuel regulations where, as here, it is "necessary or otherwise advisable" to achieve emissions standards.[39]

c. Ethanol-based High Octane Fuels Would Not Increase Other Emissions

Section 211(c)(2)(C) precludes EPA from prohibiting a fuel or fuel additive unless it makes a finding that the prohibition "will not cause the use of any other fuel or fuel additive which will produce emissions which will endanger the public health or welfare to the same or greater degree than the use of the fuel or fuel additive proposed to be prohibited."[40] As an initial matter, such an analysis would not necessarily be required because EPA would not be prohibiting any fuel or fuel additive, but rather would be controlling the octane level of the fuel. The D.C. Circuit has held that if EPA regulations merely "control" the additives in the fuel, "the findings requirement [of 211(c)(2)(C)], on its face, does not apply to the EPA action."[41] But even if EPA were to evaluate whether the new, high octane fuel was no worse than existing market fuels, an evaluation of vehicle emission performance on all pollutants, not just GHG, would be favorable. Many studies have demonstrated that high octane mid-level ethanol blends, especially those produced via "splash blending," reduce emissions of other important pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM).[42]

d. EPA Could Also Indirectly Increase Octane Levels by Facilitating Mid-Level Ethanol Blends Under Section 211(f)

RFA supports higher octane fuel blends but recognizes that not all octane sources are equal. Ethanol provides unique benefits as an octane source. For example, ethanol's cooling effect provides additional efficiency gains.[43] Ethanol also has a lower GHG carbon intensity than petroleum, and the difference is getting larger over time.[44] According to the U.S. Department of Energy, "[w]hen the high-octane blend is made with 25%–40% ethanol by volume, this energy efficiency improvement is

---

[38] Alliance of Automobile Manufacturers, Comments on Draft Technical Assessment Report, EPA-HQ-OAR-0827, at 71 (Sept. 26, 2017).

[39] *Amoco Oil Co*, 501 F.2d at 737 ("Section 211(c)(2)…establishes a rebuttable presumption that [EPA] should maintain a laissez faire posture with regard to fuel regulation. To rebut the presumption [EPA] must determine...that fuel regulation is a necessary or otherwise advisable component in [its] overall strategy to meet the Section 202 emissions standards."). Although the case related to regulations issued under section 211(c)(1)(B), the court's rationale applies equally to reviewing regulations under section 211(c)(1)(A).

[40] 42 U.S.C. §7545(c)(2)(C).

[41] *Ethyl Corp.*, 541 F.2d at 32.

[42] *See e.g.*, Carolyn Hubbard et al., Ethanol and Air Quality: Influence of Fuel Ethanol Content on Emissions and Fuel Economic of Flexible Fuel Vehicles, 48 ENVIR. SCI. & TECH. 861, 863 (2014) (compared to E10, blends of E20, E30, and E40 had lower relative NOx emissions).

[43] *See* Oak Ridge Nat'l Laboratory, Investigation of Knock Limited Compression Ratio of Ethanol Gasoline Blends (April 12, 2010).

[44] *See* Boland. S. and Unnasch. S. (2014) Carbon Intensity of Marginal Petroleum and Corn Ethanol Fuels. Life Cycle Associates Report LCA.6075.83.2014, Prepared for Renewable Fuels Association.

potentially sufficient to offset the reduced vehicle range often associated with the decreased volumetric energy density of ethanol."[45]

As an alternative to using its broad authority in 211(c) to control octane levels of gasoline directly, section 211(f) could be used to increase octane levels indirectly by allowing mid-level ethanol blends. Section 211(f)(1) prohibits introducing into the market for the first time a new fuel or fuel additive that is "not substantially similar to any fuel or fuel additive utilized in . . .certification," absent a waiver pursuant to section 211(f)(4). [46] The same provision also makes it unlawful to "increase the concentration in use" of certain fuel additives—but, again, only those that are "not substantially similar to any . . . fuel additive utilized in . . . certification."[47] Until 2017, ethanol-blended fuels were not substantially similar to a certification fuel additive, because the gasoline certification fuel contained no ethanol, and EPA's original waiver for E10 was limited to that "specified concentration" of ethanol. Beginning this year, however, the gasoline emissions certification fuel now contains 10 percent ethanol.[48] Because ethanol is a "fuel additive utilized in . . . certification," section 211(f)(1) arguably no longer limits ethanol blending in market fuel. Whatever range of interpretations it may allow, the term "substantially similar" cannot reasonably be interpreted to exclude fuel additives that are identical to those used in certification. At the very least, now that vehicle emissions certification fuel contains 10 percent ethanol, EPA should revisit its outdated rule interpreting "substantially similar" for purposes of section 211(f)(1). To the extent EPA wishes to impose controls on ethanol in market fuel, it may still utilize its authority under 211(c) to do so.

V. EPA should take other steps to facilitate the broad commercial introduction of HOLC fuels

At the September 6, 2017 public hearing on reconsideration of the Final Determination, EPA specifically asked stakeholders to provide recommendations regarding actions the Agency could take to best facilitate a transition from low-octane gasoline to HOLC fuels. RFA offers the following recommendations in response to EPA's request for comment.

a. Reform the petition process in 40 CFR 1065 for new certification fuels (e.g., high octane mid-level blends like E25 or E30) and eliminate unreasonable criteria for approval

EPA's Tier 3 Motor Vehicle Emission and Fuel Standards included provisions (codified at 40 CFR 1065.701(c)) allowing engine manufacturers to petition the Agency for approval of an alternative certification fuel, including fuels with "higher octane [and] higher ethanol content" than the prescribed test fuel.[49] While we strongly support a petition process for alternative certification

[45] Kristi Moriarty, National Renewable Energy Laboratory, "High Octane Fuel: Terminal Backgrounder" at v (Feb. 2016).
[46] 42 U.S.C. §7545(f)(1).
[47] *Id.*
[48] *Control of Air Pollution From Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards*, 79 Fed. Reg. 23414, 23810 (Apr. 28, 2014), *codified at* 40 C.F.R. § 1065.710(b)(2).
[49] 79 Fed. Reg. 23528

fuels, EPA's criteria for approving such petitions are impractical, discourage innovation, and deter engine manufacturers from seeking approval of new certification fuels.

Specifically, EPA stated that petitioners seeking approval of an alternative certification fuel must demonstrate that such a fuel "would be readily available nationwide" and that "vehicles would not operate appropriately on the other available fuels."[50] These unreasonable conditions create a "chicken vs. egg" dilemma that discourages engine manufacturers from pursuing approval of new certification fuels. That is, fuel blenders and retailers will not make a fuel "readily available nationwide" unless a substantial share of automobiles on the road are certified and approved to use the fuel. But automakers cannot certify new automobiles on an alternative certification fuel unless the fuel is "readily available nationwide." This circuitous requirement virtually guarantees that engine manufacturers will be unable to secure approval of alternative certification fuels. EPA should clarify that a fuel need not be "readily available nationwide" as a condition of approval of new certification fuel petitions.

Similarly, the requirement to demonstrate that "vehicles would not operate appropriately on other available fuels" discourages flexibility and innovation, and deters engine makers from pursuing approval of alternative certification fuels. As an example, an engine manufacturer may design a high-compression ratio engine that is optimized and requires high octane fuel (e.g., 98 RON); the automaker may wish to certify the vehicle on a high octane test fuel. In this case, the key variable allowing efficient operation of this engine is the octane rating. However, that octane rating can be achieved commercially using many different gasoline blending components. Since octane rating is the key enabler of efficiency in this engine, the engine could be designed to operate appropriately both on ethanol-free premium gasoline with 98 RON octane and on splash-blended E30 with 98 RON octane. However, the current regulatory requirements to show that the vehicle "would not operate appropriately on other available fuels" would prohibit engine manufacturers from embracing flexible approaches to engine design.

b. Eliminate unnecessarily burdensome and costly requirements related to the registration process for new fuels and additives as required under 40 CFR 79.

Current regulations governing the registration of new fuels and fuel additives are unnecessarily complex and costly, and have effectively shielded incumbent motor fuels from competition. While the general requirements for registering a new fuel are prescribed in CAA 211(b) and CAA 211(f), EPA's interpretation of these provisions, and the resultant regulations promulgated by EPA, are overly expansive and burdensome. The cumbersome and costly process to register E15 (and the unwieldy conditions of EPA's approval of a CAA 211(f) waiver for E15) serves as a poignant example of the superfluous nature of EPA's administration of the fuel registration process.

First, EPA's overly narrow interpretation of what constitutes "substantially similar" under CAA 211(f) effectively prevents new fuels from obtaining registration, and forces producers of those fuels to instead pursue a waiver from CAA 211(f) requirements. EPA's restrictive interpretation that

[50] *Id.*

new fuels must have the same "elemental composition" as the gasoline used to determine compliance with emissions standards virtually guarantees that no renewable fuel or new ethanol/gasoline blend will ever be deemed "substantially similar" (incidentally, different gasolines can have distinctly different "elemental composition," yet EPA treats all gasolines as being of homogenous composition).

Thus, manufacturers of these new fuels must pursue a CAA 211(f) waiver to show that the fuel will not "cause or contribute" to the failure of emissions control devices. The process established by EPA to secure such a 211(f) waiver is lengthy, costly, and uncertain. EPA requires extensive exhaust and evaporative emissions testing over the "full useful life" of vehicles and engines, robust materials compatibility testing, and subjective "driveability" testing. These tests can cost tens of millions of dollars to perform.

Once all of the tests are completed, the manufacturer of the new fuel must submit an application with all test results to EPA. Acceptance of the materials by EPA is not guaranteed. However, if the Agency accepts the application, a public docket is established and EPA has up to 270 days to respond to the applicant. Further, EPA may decide that approval of a CAA 211(f) waiver application is conditional upon fuel manufacturers meeting additional requirements as determined by the Agency (e.g., EPA implemented an additional "misfueling mitigation" regulation as part of its CAA 211(f) waiver approval for E15).

In addition to the CAA 211(f) waiver requirements described above, the manufacturer of a new fuel must also conduct "…tests to determine potential public health and environmental effects of the fuel…" as required by CAA 211(b). Again, EPA's interpretation of this statutory requirement is overly expansive and financially exorbitant. EPA requires detailed analysis of exhaust emissions, including speciation of a wide variety of compounds. The Agency also requires animal testing to determine the potential health effects of exposure to the fuel's evaporative emissions. Finally, recently promulgated Tier 3 motor fuel regulations essentially give EPA free rein to determine whether any other additional health effects tests are needed to satisfy the requirements of CAA 211(b).

Taken together, these EPA fuel registration requirements form an arduous barrier and unreasonable standard for approval of new fuels. As a consequence, new renewable fuel blends that provide distinct and well-known environmental and human health benefits are effectively shut out of the market and incumbent fossil fuels are insulated from competition. While EPA's expansive and liberal interpretation of statutory fuel registration requirements may be prudent for entirely new or novel fuel molecules, compounds, or blends about which little is known, it is unnecessary for fuels and blends that have been thoroughly analyzed and are well understood.

Ethanol has been used as a motor fuel component for decades. The existing information and data regarding ethanol's composition, emissions impacts, materials compatibility, effects on "driveability," and health effects is more than sufficient to support EPA decision-making about registration of new gasoline/ethanol blends for use in compatible gasoline engines.

When the effects of gasoline/ethanol blends like E20, E25, and E30 are already well-known, it makes no sense for EPA to interpret the requirements of 211(b) and 211(f) as rigidly and expansively as it has done in the past for new fuels. It is time for EPA to modernize, simplify and streamline its interpretation of statutory fuel registration requirements. Doing so would truly open the market to competition, remove barriers to expanded use of renewable fuels, stimulate job creation, and drive down consumer fuel costs.

c. Update the "R-factor" for fuel economy (CAFE) compliance calculations to better represent modern engines and fuels, as recommended by the Department of Energy and numerous automakers.

EPA incorporates the use of a so-called "R-factor" in fuel economy calculations in order to address concerns about the impacts of test fuel property variations on corporate average fuel economy (CAFE) compliance. The R-factor is defined as the ratio of the percent change in fuel economy to the percent change in volumetric heating value for tests conducted using two differing fuels.

Based on outdated 1980s-era vehicle testing data, EPA requires that automakers use an R-factor of 0.6 in CAFE compliance calculations. However, recent reassessments of the R-factor were conducted to determine the impacts of adjustments to the properties of certification gasoline under EPA's Tier 3 regulations. Specifically, the new Tier 3 certification fuel contains 10% ethanol by volume, and EPA allows automakers to petition the Agency for approval to use certification fuels with even higher levels of ethanol (e.g. 25% or 30% ethanol by volume). Because ethanol has a lower heating value than gasoline, the inclusion of ethanol in certification fuels is expected to result in a significant deviation from the CAFE baseline test fuel heating value. Thus, the accuracy of the R-factor in predicting fuel economy changes resulting from heating value changes becomes increasingly important. Recent studies by Oak Ridge National Laboratory, Ford Motor Company, and others have found that the R-factor for modern engines and vehicles is very close to 1.0.[51] Based on these findings, many stakeholders encouraged EPA to raise the R-factor to 1.0 during the Tier 3 public notice and comment period. However, the Agency has so far neglected to adjust the R-factor to account for the efficiency of modern engines.

EPA's continued failure to raise the R-factor serves to discourage automakers from pursuing certification and commercialization of engines designed to operate on higher levels of ethanol. In fact, using the EPA-required R-factor of 0.6 instead of 1.0 would result in a substantial 4.7% certification fuel economy penalty for a vehicle designed for E30 and a 2.4% penalty for using E15.[52]

---

[51] *See*, Sluder, C., West, B., Butler, A., Mitcham, A. et al., "Determination of the R Factor for Fuel Economy Calculations Using Ethanol-Blended Fuels over Two Test Cycles," *SAE Int. J. Fuels Lubr.* 7(2):551-562, 2014, doi:10.4271/2014-01-1572; and Sluder, C. Scott and Brian H. West. Oak Ridge National Laboratory. "Preliminary Examination of Ethanol Fuel Effects on EPA's R-factor for Vehicle Fuel Economy." June 2013. ORNL/TM-2013/198

[52] Woebkenberg, William. Mercedes-Benz Research & Development North America. "Mid-Blend Ethanol Fuels – Implementation Perspectives." Presentation to Society of Automotive Engineers. July 25, 2013.

Clearly, penalties of this magnitude are a strong deterrent to automakers interested in designing engines that are optimized to use higher-ethanol blends.

We strongly encourage EPA to revise the R-factor to 1.0, which is justified by the latest scientific literature. Doing so would encourage—rather than deter—innovation in engine design and remove yet another EPA-erected barrier to expanded renewable fuel use.

d. Revise the fuel economy formula for potential high-octane mid-level ethanol blend certification fuels

As described in a previous section of these comments, EPA regulations allow a petitioner to request the use of an alternative certification fuel. As each test fuel approved by EPA for use in certification testing has its own fuel economy formula, we request that EPA adopt the formula described below for high-octane mid-level ethanol blends (the proposed formula below is based on a potential certification fuel containing 25 percent ethanol by volume and offering 98-100 RON octane).[53]

$$mpg = \frac{(5{,}714 \times 10^4 \times CWF)}{\left[\left((CWF \times (NMOG + CH_4)) + (0.429 \times CO) + (0.273 \times CO_2)\right) \times NHV\right]} \times 1.05$$

where,

- 5174 x 10^4 = density of H_2O at 60ºF x specific gravity of 1975 reference fuel x NHV of 1975 reference fuel;
- CWF is the carbon weight fraction of the certification test fuel;
- NHV is the net heating value of the certification test fuel;
- NMOG is the non-methane organic gas [g/mi] in the exhaust gas as determined in accordance with applicable test procedures;
- CH_4 is the methane [g/mi] in the exhaust gas– CO is the carbon monoxide [g/mi] in the exhaust gas; and
- CO_2 is the carbon dioxide [g/mi] in the exhaust gas

This recommended formula is based on the current fuel economy equation for gasoline vehicles, with some important adjustments.[54] First, as addressed in earlier comments, the proposed formula corrects the current equation's R-factor to avoid falsely reporting a loss in fuel economy relative to the 1975 certification fuel.[55] Consistent with the fuel economy formula requested by

[53] 40 C.F.R. §§ 600.113-12(h) (gasoline), (i) (diesel), (j) (methanol), (k) (natural gas), (*l*) (ethanol), (m) (liquefied petroleum gas).

[54] *See id.* § 600.113-12(h)(1). The current fuel economy equation for gasoline omits oxygenated hydrocarbons, measuring pure hydrocarbons only instead. *Id.* § 600.113-12(h). "Although oxygenated hydrocarbons are an insignificant contributor to the fuel economy value, their effect has been included" in the proposed formula "by virtue of using NMOG in the equation." GM Comments, *supra* note **Error! Bookmark not defined.**, at 4.

[55] The R-factor is a measure of "how vehicles respond to changes in the energy content of the fuel." Tier 3 Rule, 79 Fed. Reg. at 23531. The current R-factor of 0.6 implies that a 10% change in the test fuel's energy content, for

automakers in the Tier 3 rulemaking, the proposed formula is calibrated to an R-factor of 1, which cancels out the illusory changes in fuel economy that would result under the current formula, from the lower energy content of a potential E25 certification fuel.[56]

Second, the proposed fuel economy formula includes a 5% multiplier (x 1.05) in recognition of the lower carbon content of the proposed certification fuel. (E25 contains approximately 5% less carbon per gallon than the current E10 certification fuel.) This multiplier would be a conservative exercise of EPA's discretion to "decide on the quantity of other fuel that is equivalent to one gallon of gasoline," as authorized by the Energy Independence and Security Act of 2007.[57] EPA has used this statutory authority to credit alternative fuels with the potential to reduce petroleum consumption.[58]

In the alternative, EPA could develop a fuel economy equation that credits ethanol for its upstream greenhouse gas emissions reduction, as the Agency has asserted authority to do.[59]

e. Level the playing field for credit generation for *all* alternative fuel vehicles, including flexible fuel vehicles (FFV), under the 2017-2025 CAFE/GHG rules.

The 2017-2025 CAFE/GHG finalized by EPA and NHTSA in 2012 created powerful and lucrative incentives for automakers to increase production of certain alternative fuel vehicles. Specifically, EPA created an "incentive multiplier" for all electric vehicles (EVs), plug-in electric vehicles (PHEVs), fuel cell vehicles (FCVs) and compressed natural gas vehicles (CNGVs) sold in model year 2017-2021.[60] In essence, the incentive multiplier allows these alternative fuel vehicles to count as more than one vehicle in the manufacturer's GHG compliance calculation (meaning

---

example, causes only a 6% change in vehicle fuel economy. *Id.* As demonstrated by Oak Ridge National Laboratory, the current R-factor is too low. Oak Ridge Nat'l Lab., Preliminary Examination of Ethanol Fuel Effects on EPA's R-factor for Vehicle Fuel Economy 12 (2013) ("The current factor of 0.6 which is called out in CFR is clearly too low, and a proper factor for modern vehicles is closer to unity, as might be expected from improved air/fuel ratio control common for more modern vehicles."). This means that the illusory fuel economy losses generated by changes in the energy content of the test fuel are not fully cancelled under the current equation, as required by law. *See* 26 U.S.C. § 4064(c) ("Fuel economy . . . shall be measured in accordance with testing and calculation procedures . . . utilized by the EPA Administrator for model year 1975 . . . or procedures which yield comparable results."). EPA has recognized that the R-factor is in need of correction. *See* 2012 CAFE/GHG Rule, 77 Fed. Reg. at 62777–78 ("If the certification test fuel is changed to include ethanol through a future rulemaking, EPA would be required under EPCA to address the need for a test procedure adjustment to preserve the level of stringency of the CAFE standards. EPA is committed to doing so in a timely manner to ensure that any change in certification fuel will not affect the stringency of future GHG emission standards.").

[56] Auto Alliance Tier 3 Comments, *supra* note **Error! Bookmark not defined.**, at 98; Ford Comments, *supra* note **Error! Bookmark not defined.**, at 4; GM Comments, *supra* note **Error! Bookmark not defined.Error! Bookmark not defined.**, at 4.

[57] 49 U.S.C. § 32904(c) (authorizing EPA to "decide on the quantity of other fuel that is equivalent to one gallon of gasoline").

[58] Response to Comments on the 2012 CAFE Rule, at 6-164.

[59] *See* 2012 CAFE/GHG Rule, 77 Fed. Reg. 62624, 62819 (Oct. 15, 2012) ("EPA . . . believes that although section 202(a)(1) of the Clean Air Act does not require the inclusion of upstream GHG emissions in these regulations, the discretion afforded under this provision allows EPA to consider upstream GHG emissions"); 2010 CAFE/GHG Rule, 75 Fed. Reg. 25,437 (May 7, 2010) ("EPA is reasonably and fairly accounting for the incremental increase in upstream GHG emissions from both the electric vehicles and the conventional vehicles.").

[60] 77 Fed. Reg. 62628

emissions from one vehicle are spread across multiple vehicles, diluting the emissions value per vehicle). In addition, EPA entirely ignored the upstream (well-to-tank "lifecycle") emissions impacts of electricity production and set the emissions value for EVs at 0 grams of CO2/mile.[61] EPA further provided generous "utility factors" to dual-fueled CNGVs and PHEVs, which assume those vehicles will be fueled with the lower-GHG alternative fuel most of the time.

Meanwhile, the provisions of the 2017-2025 CAFE/GHG rules strongly discourage automakers from further production of FFVs. For FFVs, EPA originally proposed requiring automakers to demonstrate actual usage of alternative fuel in the vehicle in order to generate the associated credit toward compliance with GHG standards. Of course, this is impractical and unreasonable, so EPA also finalized an alternative approach whereby the Agency would issue "early guidance" to automakers establishing a standard E85 utility factor ("F factor") based on national weighted average E85 consumption.[62]

In early 2013, EPA issued a draft of its first "early guidance" document outlining the FFV weighting factor to be used for Model Years 2016-2019. The EPA draft proposed an F factor of 0.2, meaning EPA projected that 20% of a MY 2016-2019 FFV's lifetime miles would be driven on E85.[63] Several stakeholder groups, including RFA, commented on the draft guidance and demonstrated why a higher F factor in the range of 0.4-0.6 was warranted.[64] In response to these comments, EPA issued final guidance in late 2014 that further reduced the F factor for MY 2016-2018 FFVs to just 0.14.[65] Meanwhile, EPA discontinued in MY2015 the use of a separate incentive—the 0.15 "alternative fuel economy divisor" factor—which in the past strongly encouraged FFV production. Thus, the 2017-2025 standards provide almost no incentive to automakers to build FFVs, while other alternative fuel vehicles receive generous credits and incentives. The impacts of EPA's discriminatory credit regimen are already being felt in the marketplace—FFV production in MY2015 was down nearly 1 million vehicles, or 34%, from the record output level in MY2014, according to EPA's own data.[66]

While we agree with EPA that automakers should be encouraged to produce vehicles that "[r]educ[e] petroleum consumption to improve energy security", "save the U.S. money" and "[r]educe climate change impacts,"[67] we believe incentives to stimulate the production of such vehicles should be constructed fairly and consistently. EPA should restore an equitable utility factor for FFVs in the range of 0.4-0.6 through MY2025.

---

[61] 77 Fed. Reg. 62651
[62] 77 Fed. Reg. 62830
[63] 78 Fed. Reg. 17660
[64] Comment by Bob Dinneen, President & CEO, Renewable Fuels Association re: Draft Guidance for Industry and Staff: E85 Flexible Fuel Vehicle Weighting Factor for Model Years 2016-2019 Vehicles under Light-duty Greenhouse Gas Emissions Program. April 22, 2013. (EPA-HQ-OAR-2013-0120-0008).
[65] U.S. EPA to Auto Manufacturers. "E85 Flexible Fuel Vehicle Weighting Factor for Model Year 2016-2018 Vehicles." Nov. 12, 2014.
[66] U.S. EPA. November 2016. "Greenhouse Gas Emission Standards for Light-Duty Vehicles: Manufacturer Performance Report for the 2015 Model Year." EPA-420-R-16-014
[67] 76 Fed. Reg. 75164-75165

f. Reject the results of the EPAct/V2/E-89 Fuel Effects Study and suspend further use or development of the MOVES2014 model until a new emissions study based on appropriate test fuels is conducted.

According to a number of independent third-party reviews, EPA's newest vehicle emissions modeling system (MOVES2014) is inadequate and unreliable as a tool for estimating the exhaust emissions of gasoline blends containing more than 10% ethanol. This is important because state air agencies use the MOVES modeling system to demonstrate compliance with Clean Air Act requirements. In its current condition, the model would likely discourage states from pursuing the use of higher ethanol blends as a strategy for reducing mobile source emissions.

The flaws in MOVES2014 with regard to ethanol blends stem from the model's use of data from the EPAct/V2/E-89 Fuel Effects Study. RFA strongly recommends suspending further use or development of the MOVES2014 model until a new emissions study is conducted using test fuels that more accurately represent real-world fuel blends.

In early 2016, a detailed analysis of the MOVES2014 model conducted by scientists from Wyle Laboratories and the Volpe National Transportation Systems Center concluded that, "Overall, it was found that the predictive emissions results generated by MOVES2014 for mid-level ethanol blends were sometimes inconsistent with other emissions results from the scientific literature for both exhaust emissions and evaporative emissions…results and trends from MOVES2014 for certain pollutants are often contrary to the findings of other studies and reports in the literature."[68]

Of particular concern is that the MOVES2014 model predicts increased exhaust emissions of nitrogen components and particulate matter as the ethanol content in gasoline increases, even though real-world emissions testing based on mid-level ethanol blends has shown distinctly opposite trends. "The results from other researchers often show ethanol-related emissions trends that are different than the MOVES2014 results obtained for this study…" the study found. "In some cases not only were magnitudes different but different [directional] trends were presented."[69]

The model's questionable predictions for certain emissions results from its use of data that misrepresents the actual parameters and composition of mid-level ethanol blends. Specifically, the default ethanol blend data in the MOVES2014 model is based on arcane "match blending" methods intended to "match" specific fuel parameters, rather than "splash blending" methods that are used in the real world. This data comes from the EPAct/V2/E-89 Fuel Effects Study. According to Wyle and Volpe experts, "…real-world splash blends may not have the same attributes as the modeled

[68] Wayson, R., Kim, B., and Noel, G. January 2016. "Evaluation of Ethanol Fuel Blends in EPA MOVES2014 Model." Conducted for the Renewable Fuels Association. Available at: http://ethanolrfa.org/wp-content/uploads/2016/01/RFA-MOVES-Report.pdf
[69] *Id*.

default match blends used in MOVES, and actual emissions may be different than the emissions predictions from MOVES."[70]

These likely distortions are then multiplied through the use of overly restrictive adjustment factors and equations. The authors write that "…the trends used to determine constants in the model's equations may need to consider many more variables than are now being considered," and "the adjustment factor approach may need to be more robust and consider the changes to emissions as a function of all properties, not independently." In an attempt to simulate the emissions of mid-level ethanol blends created using real-world "splash blending" practices, the Wyle and Volpe scientists performed an analysis where certain fuel parameters were modified. However, the model still produced questionable results that suggested increases in emissions of nitrogen components and PM as ethanol content increases.

To correct the deficiencies with the MOVES2014 model, the Wyle and Volpe scientists recommend obtaining new mid-level ethanol blend emissions data using blends that better represent real-world fuel properties and blending practices. They write that "…additional vehicle exhaust testing from mid-level ethanol blends with well-defined fuel properties is recommended." RFA agrees with the conclusions and recommendations of the Wyle/Volpe study and encourages EPA to suspend further usage of the MOVES2014 model until a new emissions study is conducted.

[70] *Id*., see also: J.E. Anderson, T.J. Wallington, R.A. Stein, W.M. Studzinski, "Issues with T50 and T90 as Match Criteria for Ethanol-Gasoline Blends," SAE Int. J. Fuels Lubr. 7(3):2014, doi:10.4271/2014-01-9080, November, 2014.

ATTACHMENT A

Comments of the Renewable Fuels Association (RFA) in response to Notice of Availability of Midterm Evaluation Draft Technical Assessment Report for Model Year 2022–2025 Light Duty Vehicle GHG Emissions and CAFE Standards (81 Fed. Reg. 49,217; July 27, 2016)

RENEWABLE FUELS ASSOCIATION

September 26, 2016

Attention: Docket ID No. EPA–HQ–OAR–2015–0827
Docket ID No. NHTSA–2016–0068

U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW
Washington, DC 20460

National Highway Traffic Safety Administration
1200 New Jersey Avenue SE
Washington, DC 20590

RE: *Comments of the Renewable Fuels Association (RFA) in response to Notice of Availability of Midterm Evaluation Draft Technical Assessment Report for Model Year 2022–2025 Light Duty Vehicle GHG Emissions and CAFE Standards (81 Fed. Reg. 49,217; July 27, 2016)*

The Renewable Fuels Association (RFA) appreciates the opportunity to comment on the Draft Technical Assessment Report (TAR) published by the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) in July 2016.

RFA is the leading trade association for America's ethanol industry. Its mission is to advance the development, production, and use of fuel ethanol by strengthening America's ethanol industry and raising awareness about the benefits of renewable fuels. Founded in 1981, RFA serves as the premier meeting ground for industry leaders and supporters. RFA's 300-plus members are working to help America become cleaner, safer, more energy secure, and economically vibrant.

I. Executive Summary

In 2012, EPA and NHTSA promulgated final regulations establishing corporate average fuel economy (CAFE) and greenhouse gas (GHG) emissions standards for model year (MY) 2017-2025 light-duty vehicles (LDVs). Included in the 2012 final rule was a regulatory requirement for the agencies to conduct a Midterm Evaluation (MTE) of the standards established for MY2022-2025. Through the MTE, the agencies must determine whether the MY2022-2025 standards established in 2012 are still appropriate in light of the latest available data and information.

The first step in the MTE process was the July 2016 release of a Draft Technical Assessment Report (TAR) for public comment. The TAR examines a wide range of technical issues relevant to the GHG emission and augural CAFE standards for MY2022-2025, including assessments of technology effectiveness and cost, as well as modeling of various compliance scenarios. EPA and NHTSA state that the information in the TAR and the comments received in response to the document "will inform the agencies' subsequent determination and rulemaking actions."[1] Further, they commit to "fully consider public comments on this Draft TAR as they continue to update and refine the analyses for further steps in the MTE process."[2] RFA has reviewed the TAR and has also commissioned a technical analysis of the TAR by Ricardo, Inc. (Attachment A), an engineering and technical consultancy with expertise in automotive technologies. Our examination of the TAR, along with Ricardo's analysis, leads to the following main conclusions:

[1] EPA, NHTSA, CARB. July 2016. Draft TAR, at ES-2.
[2] *Id*., at ES-2.

- Many of the advanced internal combustion (IC) engine technologies examined in the TAR implicitly call for liquid fuels with higher octane than is offered by today's regular gasoline.
- While the TAR examines various advanced IC engine technologies, it fails to simultaneously examine the fuels that *enable* those engine technologies. In general, the TAR fails to treat IC engines and liquid fuels as integrated systems, even though fuel properties can have significant effects on fuel economy and emissions.
- The TAR ignores the influence on fuels of other public policies, like the Renewable Fuel Standard (RFS), aimed at reducing petroleum consumption and GHG emissions.
- Pairing the advanced IC engine technologies examined in the TAR with high octane low carbon (HOLC) fuels with 98-100 RON octane would result in greater fuel economy and emissions benefits than considered by EPA and NHTSA.
- Use of an ethanol-based HOLC in optimized IC engines would be the lowest cost means of achieving compliance with CAFE and GHG standards for MY2022-2025 and beyond.

At the conclusion of these comments, RFA offers a number of recommendations for EPA and NHTSA's forthcoming "Proposed Determination" and the remainder of the MTE process. Chief among them are suggestions that EPA and NHTSA treat engines and fuels as integrated systems during the MTE process, and that the agencies "heed the call" from automakers, government scientists, expert panels, and academia to establish a regulatory roadmap for the broad commercial introduction of HOLC fuels to enable advanced IC engines no later than 2025.

These comments and recommendations are discussed more fully below.

II. Internal combustion engines will continue to serve as the predominant propulsion technology for light duty vehicles through 2025 and beyond

Much like the 2012 final rule, the TAR concludes that internal combustion (IC) engines powered by liquid fuels will continue to serve as the most prevalent propulsion technology for LDVs, stating that only "modest levels" of strong hybridization and "very low levels" of full electrification (plug-in vehicles) are expected by 2025.[3]

Further, the agencies determine that the efficiency of modern IC engines can be significantly improved through increased adoption of incremental technologies that exist today or are near commercialization.[4] These technologies, and their likely impacts on efficiency and CO_2 emissions, are discussed in great detail in Chapter 5 of the TAR. Several of these newer IC engine technologies (including "higher compression ratio, naturally aspirated gasoline engines") were not originally considered by the agencies for the 2012 final rule.[5] According to EPA and NHTSA, these modest IC engine improvements can enable compliance with MY2022-2025 fuel economy and GHG emissions standards: "The agencies' analyses each project that the MY2022-2025 standards can be met largely through improvements in gasoline

[3] *Id*., at ES-2.

[4] *Id*., at 5-12 ("[i]nternal combustion engine improvements continue to be a major focus in improving the overall efficiency of light-duty vehicles." and "Vehicle manufacturers have more choices of technology for internal combustion engines than at any previous time in automotive history and more control over engine operation and combustion.")

[5] *Id*., at ES-4 ("Beyond the technologies the agencies considered in the 2012 final rule, manufacturers are now employing several technologies, such as higher compression ratio, naturally aspirated gasoline engines, and greater penetration of continuously variable transmissions (CVTs); other new technologies are under active development and are expected to be in the fleet well before MY2025.")

vehicle technologies, such as improvements in engines….”[6] Indeed, the agencies project market penetration rates of just 2-3% or less will be necessary for full hybrids, plug-in hybrid electric vehicles, and battery electric vehicles to meet the MY2025 standards, while penetration rates of 33-54% are expected for certain advanced IC engine technologies.[7]

The agencies’ views that IC engines will continue as the predominant powertrain technology through at least 2025, and that significant gains in IC engine efficiency are likely, are consistent with the positions of leading experts in the automotive engineering field. Moreover, the agencies’ analysis showing that the costs of key advanced IC technologies are lower than costs for other powertrain options is also generally aligned with stakeholder positions. According to Paul Whitaker, powertrain and technical director for AVL Power Train Engineering, “We see big efficiency improvements with (IC) engines today and see the potential for lots more in the future, and they are very inexpensive relative to the other options.”[8] Additionally, the U.S. Department of Energy (DOE) states that “…vehicles with internal combustion engines will continue to comprise a significant portion of the nation’s vehicle fleet for the next several decades.”[9] Further, the National Research Council (NRC) states, “…spark-ignition engines are expected to be dominant beyond 2025.”[10]

RFA agrees with the TAR’s overarching conclusions that IC engines will continue to be the predominant LDV propulsion technology through 2025 and beyond, that further improvements in IC engine efficiency are imminent, and that such improvements are relatively low cost in comparison to other options.

III. Many of the advanced IC engine technologies examined in the TAR implicitly call for fuels with higher octane ratings than today’s regular grade gasoline

The TAR examines in detail a number of advanced IC engine technologies that are expected to facilitate compliance with MY2022-2025 CAFE and GHG standards. However, as discussed in subsequent sections of these comments, the TAR’s examination of these engine technologies does not generally include analysis of the effects of fuel properties—such as octane rating—on fuel efficiency and emissions.

a. EPA and NHTSA examine various advanced IC engine technologies, but fail to simultaneously examine the fuels that enable those engine technologies

Ricardo’s analysis of the TAR (Attachment A) shows that many of the advanced IC engine technologies examined by EPA and NHTSA would experience increased fuel efficiency and generate fewer emissions if operating on fuels with higher octane ratings than today’s regular 87 AKI gasoline. According to the Ricardo report, “…the TAR does examine in detail a number of advanced spark-ignition engine technologies that would clearly produce greater fuel economy and emissions benefits when using higher octane mid-level ethanol blends than regular gasoline.” Ricardo cites gasoline direct injection (GDI), turbocharging, downsizing, cylinder deactivation and higher compression ratio, naturally aspirated (HCR NA) engines as technologies examined in the TAR that would “benefit further from high octane fuels.”

In examining the TAR’s discussion on GDI, turbocharging, downsizing and cylinder deactivation, Ricardo concluded, “These technologies are used to increase the average load on the engine, and therefore

---

[6] *Id*., at ES-9.
[7] *Id*., Table ES-3 at ES-10
[8] Detroit Public Television. Aug. 21, 2016. *Autoline with John McElroy*. Episode #2026 (“Deep Freeze for the ICE?”)
[9] U.S. Department of Energy. *Co-Optimization of Fuels & Engines for Tomorrow’s Energy-Efficient Vehicles.* Available at: http://www.nrel.gov/docs/fy16osti/66146.pdf
[10] National Research Council, Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles. June 2015. *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles,* at S-4.

make it more prone to knocking. Because the engine tends to run more often at or near a knock-limited condition, it can take advantage of a high octane fuel." As Ricardo explains, GDI and turbocharging are "…often employed together in a downsized engine package because the in-cylinder charge cooling effect from GDI helps to mitigate the knocking tendency." The TAR shows that market penetration rates for GDI and turbocharging have expanded rapidly in recent years, with GDI growing from 2% of the market to 45% between MY2008 in MY2015 and turbocharging growing from 3% to 18% in the same timeframe. EPA and NHTSA expect more than 90% of IC engines to employ GDI and turbocharging by MY2025.[11]

The TAR also discusses emerging Atkinson cycle and Miller cycle engine technologies, both of which would also operate more efficiently on high octane fuels, according to the Ricardo report. And while it may not seem immediately obvious, Ricardo reports that even advanced technologies like variable compression ratio, certain transmission technologies, and even hybrid electric vehicles (when operating on engine power) would benefit from the use of a higher octane fuel.

The technology discussed in the TAR that is most reliant on higher octane is HCR NA engines. EPA projects that HCR NA engines will need to penetrate 44% of the light duty vehicle market by 2025 to facilitate compliance with CAFE and GHG standards.[12] However, according to Ricardo, "…compression ratios *cannot be increased with existing engine technologies using our current standard gasoline octane ratings* and even more so with engine technologies that are expected to be increasingly utilized in the future, such as downsizing and boosting." Similarly, the NRC cites "currently available octane levels" as the key "limitation on [increasing] compression ratio."[13] Thus, it is somewhat puzzling that EPA would include such heavy reliance on HCR NA engines in the TAR without any accompanying discussion of the fuels and octane ratings necessary to enable this technology.

Collectively, these current and emerging engine technologies point to the need for a higher octane rating for regular gasoline. Indeed, the effectiveness of future advanced IC engines in improving fuel economy and reducing emissions will in part be determined by the octane rating of the liquid fuels they use. The use of high octane fuels in these engines would ensure they produce the maximum possible fuel economy and emissions reductions.

b. Increased use of certain advanced IC engine technologies has *already* resulted in greater demand for higher octane fuels

Growth in turbocharging has already resulted in increased demand for higher-octane fuels, according to recent analysis by the Energy Information Administration (EIA).[14] The EIA analysis suggests that more stringent CAFE and GHG standards caused automakers to increase the market penetration of turbocharging from 3.3% in MY2009 to 17.6% in MY2014. The surge in turbocharging was accompanied by an increase in the demand for high octane premium gasoline, according to EIA. In fact, premium gasoline sales rose from 7.8% of total gasoline sales in June 2008 to 11.3% of total gasoline sales by September 2015.

According to the EIA analysis, "As automakers produce more vehicles with turbocharged engines, it is likely they will recommend or require more LDVs to use higher-octane gasoline. Premium gasoline sales as a percent of total gasoline sales are likely to increase as more car models either recommend or require premium gasoline. This increase is expected to continue as automakers increase the use of turbocharging as one strategy to comply with increasingly stringent fuel economy standards."

---

[11] EPA, NHTSA, CARB. July 2016. Draft TAR, Figure 3.10 and 3.11 at 3-12
[12] *Id*., Table ES-3 at ES-10.
[13] NRC. June 2015 at S-4.
[14] EIA. April 6, 2016. *Engine design trends lead to increased demand for higher-octane gasoline.*

The EIA report is corroborated by analysis performed by MathPro, Inc., a consulting firm that specializes in petroleum refining economics.[15] MathPro's analysis shows that the average pool-wide octane rating for gasoline increased from approximately 88.2 AKI in 2009 to 88.5 in 2015, largely as a result of increased sales of vehicles requiring or recommending the use of premium gasoline. In examining the TAR's projections of future advanced IC engine technology deployment, MathPro concluded that greater use of higher compression ratio and turbocharging will "substantially increase the call for octane."

Based on projected growth in turbocharging alone, MathPro calculated that premium gasoline could account for 17-22% of total gasoline sales by 2025, depending on varying levels of consumer adherence to the auto manufacturers' fueling recommendations. According to MathPro, "By itself, increasing the use of turbocharging could increase the required average octane of the gasoline pool by 0.3-0.6 numbers (AKI), depending on consumer response to fueling recommendations." Notably, this MathPro analysis does not account for the impact of HCR, which would further intensify the call for octane. EPA projects HCR NA engine technology will need to penetrate 44% of the market by MY2025 (compared to 3% or less today) to facilitate compliance with the standards.

It is important to note, however, that retail prices for premium grade gasoline have annually averaged 7-16% more than regular grade gasoline prices since 2010 ($0.24-0.40/gallon).[16] This cost increase likely has deterred some owners of GDI, turbocharged vehicles from purchasing premium, even though the manufacturer recommends or requires premium. The cost discrepancy between regular and premium grade gasoline also highlights the need to leverage lower-cost sources of octane, such as ethanol.

IV. The TAR fails to treat IC engines and liquid fuels as integrated systems, even though fuel properties can have significant effects on fuel economy and emissions

By itself, the IC engine does nothing to propel a light duty vehicle or generate GHG emissions. It is only when a liquid fuel is introduced into the engine that the technology works to deliver the service of mobility. In this way, IC engines and liquid fuels combine to form a highly integrated system in which one component is useless without the other. Indeed, the IC engine's efficiency and emissions can be greatly affected by the characteristics of the liquid fuel used in the engine. Unfortunately, in assessing the technologies potentially used to meet MY2022-2025 CAFE and GHG standards, the TAR focuses almost exclusively on the engine component of this system and gives no consideration to the effect of various fuel properties on fuel economy and emissions. This is a significant shortcoming of the TAR.

a. EPA and NHTSA should follow the example of DOE, whose Co-Optima program appropriately recognizes the symbiotic relationship between fuels and engines

Recognizing that fuels and engines must be developed in concert to maximize efficiency and emissions reductions, the U.S. Department of Energy has launched an initiative to focus on "Co-optimization of Fuels and Engines for Tomorrow's Energy Efficient Vehicles." The initiative, known simply as "Co-optima," endeavors to "…simultaneously tackle fuel and engine innovation to co-optimize performance of both elements and provide dramatic and rapid cuts in fuel use and emissions."[17] Co-optima has two major research tracks, the first of which is "…improving near-term efficiency of spark-ignition engines through the identification of fuel properties and design parameters of existing base engines that

[15] MathPro, Inc. Sep. 8, 2016. *Capturing Ethanol's Octane Value in Gasoline Blending*. Webinar presentation to RFA members. (Available upon request)

[16] EIA. *Retail Gasoline Prices*. https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm Accessed Sep. 12, 2016.

[17] U.S. Department of Energy. *Co-Optimization of Fuels & Engines for Tomorrow's Energy-Efficient Vehicles.* Available at: http://www.nrel.gov/docs/fy16osti/66146.pdf

maximize performance."[18] Importantly, this track includes identifying "candidate fuels" for use in co-optimized engines to achieve peak performance, energy efficiency and emissions reductions. The "market introduction target" for co-optimized fuels and IC engines under this research track is 2025.

A recent summary of DOE research conducted as part of the Co-optima program (Attachment B) demonstrates that significant additional improvement in fuel economy and GHG emissions reduction can occur when advanced IC engines are paired with high octane low carbon (HOLC) fuels.[19] Automakers have also advocated for a coordinated approach to the development and regulation of engines and fuels. According to Dan Nicholson, vice president of global propulsion systems at GM, "Fuels and engines must be designed as a total system. It makes absolutely no sense to have fuel out of the mix."[20]

EPA and NHTSA tangentially acknowledge the importance of the Co-optima initiative in the TAR, stating that the agencies "…will continue to closely follow the Co-Optima program and provide input to DOE, including through EPA's technical representative on the Co-Optima External Advisory Board, as this program has the potential to provide meaningful data and ideas for GHG and fuel consumption reductions in the light-duty vehicle fleet for 2026 and beyond." However, this statement is the closest the TAR gets to examining future engine technologies and fuels in a holistic, systems-based manner.

b. The TAR's assumptions regarding future liquid fuels are often unclear and inconsistent

In general, the TAR does not discuss liquid fuel properties in the context of their potential effects on fuel economy and emissions. However, as part of the agencies' analysis of technology cost, effectiveness, and lead time, the TAR necessarily makes some assumptions about the liquid fuels used in advanced IC engines. Unfortunately, these fuel property assumptions—particularly with respect to octane—are often unclear, misaligned, or inconsistent with the properties of today's market fuels and, more importantly, those expected in the future. The fuel properties assumed for the TAR's engine testing, engine mapping, demonstrations of compliance, and assessments of technology effectiveness and cost often vary widely, leading to apples-to-oranges results and conclusions. Ultimately, however, the key pieces of the EPA and NHTSA analyses (e.g., demonstrations of compliance) generally assume the status quo for fuels (i.e., predominantly 87 AKI gasoline) will continue through 2025.

The TAR contains a number of examples of misaligned assumptions and testing results related to fuels generally, and octane rating specifically. EPA testing of the 2.0L and 2.5L variants of the Mazda SKYACTIV-G engine apparently used 88 AKI (91 RON) fuel with 10% ethanol (E10) and 92 AKI (96 RON) fuel without ethanol.[21] Meanwhile, testing of the Ricardo 3.2L V6 Turbocharged, GDI "EBDI" used 91 RON (87 AKI E10), but all fuel consumption results developed in this study "assumed use of U.S. Certification Gasoline (95 RON, E0)."[22] Further, the TAR states that engine mapping conducted by IAV for NHTSA "…used gasoline with LHV = 41.3 MJ/kg for the mapping but the naturally aspirated engines were calibrated with 87 (R+M)/2 rating fuel and the turbocharged engines used 93 octane fuel."[23] Despite the likelihood that manufacturers of turbocharged engines likely would require or recommend the use of 91-93 AKI retail fuels (premium grade), the NHTSA vehicle fuel economy results for turbocharged engines were adjusted to represent certification fuel by using the ratio of the lower heating values of

---

[18] *Id*.
[19] Oak Ridge National Laboratory. July 2016. *Summary of High-Octane, Mid-Level Ethanol Blends Study*. ORNL/TM-2016/42
[20] Society of Automotive Engineers. Aug. 3, 2016. *GM, Honda execs agree: Higher octane gas needed to optimize ICE efficiency.* http://articles.sae.org/14940/
[21] EPA, NHTSA, CARB. July 2016. Draft TAR, at 5-42.
[22] *Id*., at 5-281.
[23] *Id*., at 5-504.

the test and certification fuels. Apparently, this was done because "NHTSA understands that using such fuel (i.e., 93 AKI) might lead to overestimating the effectiveness of the technology, especially for high BMEP engines."[24] Thus, despite being justified in its choice to use 93 AKI fuel for turbocharged engines, NHTSA says it "…will ensure that all future engine model development is performed with regular grade octane gasoline."[25]

For the demonstration of compliance with light-duty vehicle GHG and CAFE standards, EPA chose a 93 RON (roughly 89 AKI) gasoline with no ethanol.[26] Further, the TAR states that "EPA's analysis of effectiveness with gasoline fueled engines did not include analysis of effectiveness using Tier 3 certification gasoline (E10, 87 AKI) although protection for operation in-use on 87 AKI E10 gasoline was included in the analysis of engine technologies considered both within the original FRM and within the Draft TAR."[27] Finally, EPA's OMEGA modeling used "petroleum gasoline" without ethanol to determine the quantity of fuel savings, with EPA explaining that "petroleum gasoline…is different than retail fuel, which is typically blended with ethanol…"[28]

c. The TAR ignores the influence on fuels of other public policies aimed at reducing petroleum consumption and GHG emissions

EPA administers a number of other regulatory programs focused on fuels and GHG emissions, the most notable of which is the Renewable Fuel Standard (RFS). The RFS is responsible for rapid growth in the use of ethanol and other biofuels since 2005, and today ethanol represents 10% of U.S. gasoline consumption. Further increases in renewable fuel production and use in the future are required under the RFS, meaning larger volumes of ethanol will be available through the 2025 timeframe. Given that ethanol represents a large and growing portion of the U.S. gasoline pool, it is unfathomable that EPA and NHTSA would use gasoline with no ethanol to model compliance scenarios for the MY2022-2025 CAFE and GHG standards. In reality, the RFS will continue to drive investment and innovation in renewable fuel technologies, and high-octane ethanol will represent an increasing share of the gasoline pool through 2025 and beyond. The impacts of the RFS and other regulations on the composition and mix of the U.S. gasoline pool should be considered by EPA and NHTSA throughout the MTE process.

The TAR also ignores the potential impacts of EPA's Tier 3 fuel regulations, which include a provision allowing automakers to potentially certify new vehicles to HOLC fuels. Indeed, the Tier 3 regulation cites E30 as a potential HOLC that could improve engine efficiency: "…we allow vehicle manufacturers to request approval for an alternative certification fuel such as a high-octane 30 percent ethanol by volume blend (E30) for vehicles that may be optimized for such fuel. …This could help manufacturers who wish to raise compression ratios to improve vehicle efficiency as a step toward complying with the 2017 and later light-duty greenhouse gas and CAFE standards."[29]

Finally, by failing to consider the fuels that will enable these new technologies, the agencies miss an opportunity to address another critically important public policy priority – reducing global climate change. This Administration has made reducing GHG emissions a priority, as evidenced by its leadership at last year's Paris Climate Change Conference (COP21). But it is clear now that we can't address climate change by attacking coal and power generation alone, as the Administration's plan submitted to the UN

[24] *Id*., at 5-509.
[25] *Id*., at 5-512.
[26] *Id*., Table 5.33 at 5-227.
[27] *Id*. at 5-228.
[28] *Id*., at 12-60.
[29] 79 FR 23,424 and 23,528.

appears to do. Transportation is now the single largest source of U.S. GHG emissions.[30] Promoting fuels that reduce GHG emissions, such as ethanol, must be a part of any successful climate change policy.

In summary, the TAR generally omits discussion on the potential effects of various liquid fuel properties, such as octane rating, on engine efficiency or emissions. However, certain elements of the TAR (e.g. engine tests, engine mapping, etc.) required EPA and NHTSA to make assumptions about the fuels used in future IC engines; in these instances, assumptions about fuel properties were often found to be unclear, inconsistent, or not representative of current and future expectations regarding marketplace fuels. Further, the agencies ignore the significant influence of other regulatory programs, like the RFS, on the current and future composition and mix of U.S. fuels.

Because liquid fuels and IC engines act as integrated systems, the EPA and NHTSA should ensure any other analyses conducted for the MTE properly consider both the impacts of the fuel and the engine on fuel efficiency and emissions. Further, EPA and NHTSA should, to the extent possible, use consistent assumptions about future fuel properties when conducting engine testing and mapping, compliance demonstrations, cost modeling, and other analyses for the MTE.

V. Pairing the advanced IC engine technologies examined in the TAR with high octane low carbon (HOLC) fuels would result in greater fuel economy and emissions benefits than considered by EPA and NHTSA.

As underscored elsewhere in these comments, the TAR examines only the potential fuel economy and emissions improvements expected to result from adoption of various advanced IC engine technologies. The TAR does not consider the ability of high octane low carbon (HOLC) fuels to multiply these fuel economy and emissions improvements. In essence, the TAR assumes the status quo for liquid fuels, meaning significant additional fuel economy improvements and emissions reductions are overlooked.

According to the attached Ricardo report, "…many of the technologies that are discussed in the Draft TAR, including the ones with the highest expected penetration rates, could produce *greater* GHG and fuel economy benefits if paired with fuels offering higher octane ratings than contemplated by EPA and NHTSA for the agencies' modeling exercises."

Numerous studies by the automotive industry, DOE, and academia have examined the efficiency gains and emissions reductions that can be achieved when HOLC fuels is used in an IC engine with HCR, turbocharging, and other advanced technologies discussed in the TAR. These studies have repeatedly shown that a high octane fuels (98-100 RON) used in HCR engines improves efficiency and reduces emissions by 4-10%, depending on drive cycle and other factors. Studies using a high octane mid-level ethanol blend also demonstrate that fuel economy and vehicle range using HOLC blends like E25 and E30 is equivalent or superior to performance using E10, even though the E25 and E30 blends have lower energy density. Many of these studies are discussed in detail in Attachments A, B, and C.

a. Ethanol's unique properties make it an attractive candidate for boosting octane in future HOLC fuel blends

Certain chemical properties, such as "sensitivity" and heat of vaporization, make some octane boosters more attractive than others. As researchers have examined different methods of boosting gasoline octane ratings, one option—increased levels of ethanol—has stood out as the most efficient and economical pathway.

Not only does ethanol offer extremely high octane (109 RON, 91 MON), it also features high sensitivity and high heat of vaporization. These are attractive properties that, when considered along with

[30] EIA, *Monthly Energy Review*, July 2016, p. 176.

ethanol's lower "lifecycle" carbon intensity and lower cost relative to other octane options, make ethanol the clear choice for future HOLC fuels. The importance of octane sensitivity and heat of vaporization are discussed in great detail in the Ricardo report (Attachment A). Ricardo states that these benefits are important considerations for "…DI engines especially, both NA and turbocharged, which are expected to comprise the majority of future engines for both conventional and hybrid vehicles."

In addition to the tailpipe CO_2 reductions observed in several of the studies cited in these comments, ethanol-based HOLC fuels also offer important lifecycle GHG emissions benefits. That is, the total "well-to-wheels" (WTW) emissions associated with producing and using ethanol are significantly lower per unit of energy delivered than the emissions resulting from petroleum production and use. The latest analysis conducted by DOE's Argonne National Laboratory found that today's corn ethanol reduces GHG emissions by an average of 34-44% compared to petroleum, while emerging cellulosic ethanol technologies offer GHG reductions of 88-108%.[31] These benefits are compounded when the ethanol is used in a HOLC fuel that achieves greater fuel economy and vehicle range (i.e., more miles with less energy) than today's marketplace fuels.

In a recent study, Argonne National Laboratory examined the WTW GHG emissions impacts of HOLC fuels (100 RON) containing 25% and 40% ethanol.[32] The analysis found that the inherent efficiencies resulting from using a high octane fuel in a HCR engine alone resulted in a 4-8% reduction in GHG emissions per mile compared to baseline E10 gasoline vehicles. Additional GHG reductions of 4-9% were realized as a result of corn ethanol's lower lifecycle emissions upstream, meaning total GHG emissions per mile were 8% and 17% lower for E25 and E40, respectively, compared to baseline E10. Meanwhile, E25 and E40 HOLC blends made with cellulosic ethanol were shown to reduce total WTW GHG emissions by 16-31% per mile compared to E10. While high octane fuels using petroleum-derived octane sources may provide similar tailpipe CO_2 reductions as ethanol-based HOLC fuels, they clearly do not offer the additional GHG reductions associated with ethanol's full WTW lifecycle.

Additional studies show that using ethanol as the source of octane in future high octane fuels has the potential to significantly decrease petroleum refinery GHG emissions by reducing the energy intensity of the refining process.[33]

b. Use of an ethanol-based HOLC in optimized IC engines would be the lowest cost means of achieving compliance with CAFE and GHG standards for MY2022-2025 and beyond

A central objective of the TAR is to estimate the potential costs associated with various technology pathways for achieving the MY2022-2025 CAFE and GHG standards. Again, however, the TAR tends to examine only the expected costs associated with various engine and vehicle technologies, with little or no consideration given to the associated fuel costs over the vehicle's life.

---

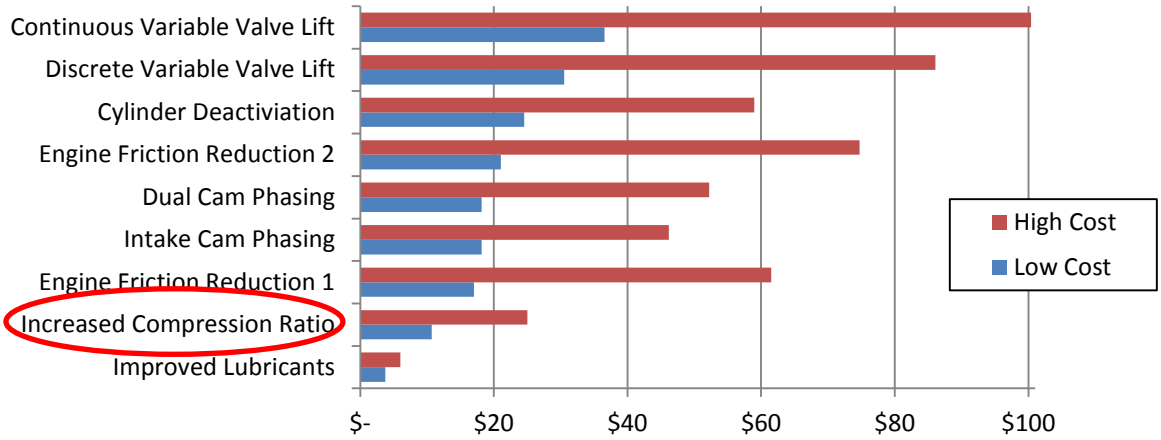
[31] Wang, M.; Han, J.; Dunn, J. B.; Cai, H.; Elgowainy, A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environ. Res. Lett. 2012, 7, 1–13, DOI: 10.1088/1748-9326/7/4/045905

[32] Oak Ridge National Laboratory. July 2016. *Summary of High-Octane, Mid-Level Ethanol Blends Study*. ORNL/TM-2016/42

[33] See "Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content", DS Hirshfeld, JA Kolb, JE Anderson, W Studzinski, and J Frusti. (2014) dx.doi.org/10.1021/es5021668 | Environ. Sci. Technol. 2014, 48, 11064-11071; and "Petroleum refinery greenhouse gas emission variation related to higher ethanol blends at different gasoline octane rating and pool volume levels", V Kwasniewski, J Blieszner, and R Nelson, DOI: 10.1002/bbb.1612; Biofuels, Bioprod. Bioref (2015)

When only the costs of various engine technologies are considered, HCR stands out as one of the most cost-effective means available for increasing engine efficiency (Figure 1).

Figure 1. Cost per Percentage Point Increase in Engine Efficiency



Based on NRC (June 2015); Draft TAR (July 2016); AIR, Inc. (Sep. 2016)

The National Research Council estimates that the cost to the automaker to introduce higher compression ratio for use with "higher octane regular fuel" is likely $75-150 per vehicle.[34] However, analysis by Air Improvement Resource, Inc. (Attachment C) suggests "…costs of increased compression ratio would be near zero, especially if it were accomplished during normal engine re-design cycles." Similarly, Ricardo (Attachment A) notes that "Since the costs to an OEM for increasing compression ratio are minimal for a new engine design, it is clear that implementing a high octane mid-level ethanol fuel standard would be the lowest cost technology and have even greater benefits in real world driving."

Still, the engine technology cost is only one-half of the equation when total vehicle purchase and operation costs are considered; fuel costs must also be considered. To examine the total cost of high compression ratio engines using a HOLC fuel (98 RON E25) as a technology pathway for compliance with 2022-2025 CAFE and GHG standards, Air Improvement Resource, Inc. (AIR) conducted a study (Attachment C) using the same OMEGA model used by EPA and NHTSA for the TAR. The AIR study found that this pathway can substantially reduce the cost of compliance with the standards, concluding that "With higher compression ratio engines included, total costs of the 2025 model year standards are reduced from $23.4 billion to $16.8 billion. …This analysis has shown that if a high octane mid-level blend ethanol fuel such as 98-RON E25 were an option for model year 2022-2025 vehicles meeting EPA's GHG standards, overall program costs would be significantly reduced."

c. Increasing octane should not come at the expense of air quality, carbon emissions, or human health

The potential for significant environmental, economic, and public health benefits from introducing higher octane fuels is obvious. However, the transition to higher octane fuels must be accompanied by requirements that octane sources improve air quality, reduce carbon emissions, and protect public health. Without such protections, there is the potential that increasing gasoline octane could result in unnecessary backsliding on criteria air pollutants, air toxics, and other harmful emissions linked to certain high-octane hydrocarbons. When it comes to air quality and human health, not all octane sources are created equal. Ethanol reduces criteria pollutants, and is the only source of octane that is truly renewable and results in a significant reduction in carbon. But much of the octane contribution in

[34] NRC. June 2015. TABLE S.2 NRC Committee's Estimated 2025 MY Direct Manufacturing Costs of Technologies

today's gasoline comes from petroleum-derived aromatic hydrocarbons such as benzene, toluene, and the C8 aromatics like xylene. Those sources of octane are far from benign.

The health impacts of aromatic hydrocarbons are well known. A 2015 study published in the *American Journal of Epidemiology* linked benzene found in traffic emissions to childhood leukemia. A 2012 study published by the University of California ties the risk of autism to toxics found in traffic pollution. And a 2015 study published in the *Journal of Environmental Health Perspectives* links microscopic toxic particles in car exhaust to heart disease. Aromatic hydrocarbons compose 20-50% of the non-methane hydrocarbons in urban air and are considered to be one of the major precursors to urban secondary organic aerosols (SOA). SOA is a form of fine particulate matter pollution (PM2.5), which is widely viewed as the most lethal air pollutant in the U.S. today. Moreover, new evidence is confirming that particulate matter from gasoline exhaust is a major source of black carbon, which is thought to be a significant contributor to climate change.

To date, EPA has been relatively quiet on the growing health and environmental threat posed by increased aromatics in gasoline. Because increasingly stringent fuel economy and GHG standards will likely result in increased use of higher octane fuels, the EPA must take into consideration the ancillary health and climate impacts of the various octane sources, and assure that no backsliding can occur.

VI. Automotive engineers and executives, Department of Energy researchers, the National Research Council, and academia all are calling for HOLC fuels to increase fuel economy and decrease GHG emissions

Over the past several years, a growing chorus of automotive engineers and executives, government scientists, expert panels, and university researchers has called for the introduction of HOLC fuels. These experts have clearly demonstrated that HOLC fuels would enable HCR engines and other advanced IC engine technologies, which in turn would improve engine efficiency and reduce emissions. Below is a partial list of statements from these experts regarding the need for HOLC fuels.

- "Higher octane is necessary for better engine efficiency. It is a proven low-cost enabler to lower CO2; 100 RON fuel is the right fuel for the 2020-2025 timeframe."*—Dan Nicholson, vice president of global propulsion systems, GM*[35]
- "100 RON has been on the table for a long time. The only way we will ever get there is to continue to push and work in a collaborative way." *– Tony Ockelford, director of product and business strategy for powertrain operations, Ford Motor Company*[36]
- "We need to find a new equilibrium. Whether it is 98 or 100 (RON) octane, we need something at that level*."— Bob Lee, head of powertrain coordination, Fiat Chrysler*[37]
- "…it appears that substantial societal benefits may be associated with capitalizing on the inherent high octane rating of ethanol in future higher octane number ethanol-gasoline blends." *– Ford Motor Company*[38]

[35] Truett, Richard. Automotive News. April 13, 2016. *Powertrain executives press for higher octane gasoline to help meet mpg, CO2 rules.*
[36] *Id*.
[37] *Id.*
[38] J.E. Anderson et al. July 2012. *High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States*. Fuel, Volume 97: Pages 585–594.

- "…a mid-level ethanol-gasoline blend (greater than E20 and less than E40) appears to be attractive as a long-term future fuel for automotive engines in the U.S." – *AVL Powertrain Engineering and Ford Motor Company*[39]
- "There has been a big push in the industry for higher octane ratings…and it is proven that you can gain several percentage points in improvement of fuel economy if you have higher octane rating fuel available." – *Dean Tomazic, executive vice president and chief technology officer, FEV North America*[40]
- "One of the advantages without costing more on the vehicle side is to look at upping the minimum octane rating on the fuel and allowing OEMs to optimize compression ratio in engines, which would give us an efficiency benefit without actually adding cost to the whole system. …the addition of ethanol blends would be a good improvement to actually drive efficiency." – *David McShane, vice president of business development, Ricardo, Inc.*[41]
- "If we could optimize engines only to operate on premium fuel, then life would be a lot easier for us and we'd be able to see much more of a benefit in terms of efficiency. …if ethanol was widely available then our life as developers of gasoline engines would become easier." – *Paul Whitaker, powertrain & technical director, AVL Powertrain Engineering*[42]
- "(High octane fuels), specifically mid-level ethanol blends (E25-E40), could offer significant benefits for the United States. These benefits include an improvement in vehicle fuel efficiency in vehicles designed and dedicated to use the increased octane." – *Oak Ridge National Laboratory, Argonne National Laboratory, and National Renewable Energy Laboratory*[43]
- "Improvements to engine efficiency made possible with ethanol fuels may be a synergistic approach to simultaneous compliance with CAFE and RFS II. This presents a unique and infrequent opportunity to dramatically alter internal combustion engine operation by improving fuel properties." – *Oak Ridge National Laboratory*[44]
- "Several technologies beyond those considered by EPA and NHTSA might provide additional fuel consumption reductions for spark ignition engines or provide alternative approaches at possibly lower costs for achieving reductions in fuel consumption by 2025. These technologies include…higher compression ratio with higher octane regular grade gasoline…" – *National Research Council*[45]
- "[T]ransitioning the fleet to higher-octane gasoline would result in significant economic and environmental benefits through reduced gasoline consumption." – *Massachusetts Institute of Technology*[46]

---

[39] Stein, R., Anderson, J., and Wallington, T., "An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions," *SAE Int. J. Engines* 6(1):470-487, 2013, doi:10.4271/2013-01-1635.
[40] Detroit Public Television. Aug. 21, 2016. *Autoline with John McElroy*. Episode #2026 ("Deep Freeze for the ICE?")
[41] *Id*.
[42] *Id*.
[43] Oak Ridge National Laboratory. July 2016. *Summary of High-Octane, Mid-Level Ethanol Blends Study*. ORNL/TM-2016/42.
[44] Derek A. Splitter and James P. Szybist (2014) "Experimental Investigation of Spark-Ignited Combustion with High-Octane Biofuels and EGR. 2. Fuel and EGR Effects on Knock-Limited Load and Speed" *Energy & Fuels*.
[45] NRC. June 2015, at 2-84.
[46] R.L. Speth et al. Economic and environmental benefits of higher-octane gasoline. *Environ Sci Technol.* 2014 Jun 17;48(12):6561-8. doi: 10.1021/es405557p

VII. Recommendations for EPA and NHTSA's "Proposed Determination" and remainder of MTE process

EPA and NHTSA state that feedback received in response to the Draft TAR will inform the agencies' "Proposed Determination" of whether the 2022-2025 standards are appropriate. Based on the forgoing comments in this document and the overwhelming preponderance of evidence supporting introduction of HOLC fuels as a means of increasing engine efficiency and reducing emissions, we offer the following recommendations for the agencies' consideration:

a. EPA and NHTSA should treat engines and fuels as integrated systems during the MTE process and beyond

Liquid fuels and IC engines combine to form highly integrated systems. One component of this system is ineffectual without the other. Thus, any effort to examine the potential impacts of new and emerging advanced IC engine technologies on fuel economy and emissions must also take into account the effects of the fuels being used by the engines. Unfortunately, fuels are little more than an afterthought in the TAR, and where fuel-related assumptions were unavoidable, the TAR is unclear, inconsistent, conflicts with current and future expectations about in-use liquid fuels, and ignores the influence of other policies—like the RFS—on the composition and mix of motor fuels.

RFA strongly recommends that EPA and NHTSA follow the lead of DOE's Co-Optima program by treating engines and fuels as a system in the Proposed Determination and any further analysis supporting the MTE process. Specifically, the agencies should give consideration to the liquid fuel properties—such as octane—that can best enable near term, low-cost advances in IC engine technologies.

b. As a sensitivity case to the central compliance demonstrations, the agencies should assess the fuel economy and emissions impacts associated with using HOLC fuels in advanced IC engines with high compression ratios

Numerous independent studies have documented the fuel economy and emissions benefits resulting from the use of HOLC fuels in HCR and other advanced IC engine technologies. These analyses consistently show HOLC fuels (98-100 RON) in HCR engines produce efficiency gains and CO_2 reductions in the range of 4-10% compared to the use of regular grade 87 AKI gasoline in today's IC engines, depending on drive cycle and other factors. Additional upstream GHG emissions reductions mean ethanol-based HOLC fuels can reduce WTW emissions by 8-17% per mile if using today's corn ethanol, and 16-31% per mile if using emerging cellulosic ethanol.

EPA and NHTSA should examine a compliance demonstration scenario in which a significant portion of the LDV fleet uses 98-100 RON fuel in HCR engines. The agencies should further analyze the impact of various octane streams on the results of this scenario (i.e., compare a 98-100 RON mid-level ethanol blend to a 98-100 RON ethanol-free gasoline). Such analysis would greatly contribute to the understanding of the potential of HOLC fuels to multiply the efficiency and emissions benefits of advanced IC engine technologies.

c. A comprehensive cost-benefit analysis of various CAFE/GHG compliance pathways including both engine *and fuel technologies* should be conducted. Such analysis should include a pathway for HOLC fuels in advanced IC engines

The TAR provides the technical underpinnings for EPA and NHTSA's Proposed Determination of whether the 2022-2025 CAFE and GHG standards are appropriate. The implementation of these standards will have significant ramifications for the nation's economy and environment. The automotive sector will deploy billions of dollars in capital to develop and manufacture the technologies that ultimately will facilitate achievement of future fuel economy and GHG reduction standards. Consumers will feel the

impacts of these regulations as well, as automakers attempt to recoup some of their increased costs through higher retail prices for new automobiles. As discussed in these comments, the standards will also have impacts on fuel producers.

Given the economic and environmental significance of the 2022-2025 fuel economy and emissions standards, we believe EPA, NHTSA and the White House Office of Management and Budget should undertake a comprehensive cost-benefit analysis of various technology pathways for meeting the 2022-2025 standards. Critically, this analysis should include not just the engine and vehicle costs to manufacturers and consumers, but also the expected fuel costs over the life of the engine. Such analysis should be conducted for all of the various engine/vehicle technologies examined in the TAR and the corresponding fuels they use. Such an analysis also bears relevance to EPA's administrative authority to regulate octane, as EPA has stated it "…would have to show how the benefits of raising gasoline octane would justify the cost" in order to promulgate regulations requiring higher minimum octane.[47]

d. EPA and NHTSA should ensure the Proposed Determination fully accounts for the Co-Optima initiative's recommendations for "candidate fuels" that best enable advanced IC engine technologies and maximize their efficiency

A major near-term objective of the DOE's Co-Optima initiative is to identify and characterize the behavior of new "candidate fuels" that can enable greater energy efficiency and reduced emissions in optimized engines. Upon identifying and characterizing the fuels that offer the greatest potential, DOE will examine the impact of the candidate fuels' properties on engine design and the effects on performance, energy efficiency and emissions. Much of this work is already underway at DOE, and a recent report summarizing research efforts to date demonstrates that mid-level ethanol HOLC fuel blends offer great potential to improve efficiency and cut emissions in the near-term (Attachment B). However, DOE has not yet officially specified and characterized the candidate fuels that merit further research and testing. Once available, the MTE process should fully account for information from DOE pertaining to the candidate fuels best suited for use in new and emerging IC engine technologies.

e. The agencies should "heed the call" for HOLC fuels. EPA and NHTSA should use the MTE process to establish the roadmap to broad commercial introduction of HOLC fuels in advanced IC engines beginning in 2025

Consensus is building around the need for HOLC fuels to enable greater engine efficiency and reduced emissions. Automotive engineers and executives, government scientists, expert panels, and university researchers have called for a higher minimum octane rating for future fuels. These experts have clearly demonstrated that HOLC fuels would enable HCR engines and other advanced IC engine technologies, which in turn would improve engine efficiency and reduce emissions.

However, without regulatory intervention or guidance, there is no guarantee that HOLC fuels will indeed be broadly available in the marketplace to enable advanced IC engine technologies to proliferate. Many of the stakeholders calling for the introduction of HOLC fuels have also called upon EPA to use its regulatory authority to establish a minimum octane rating for future gasoline. The Alliance of Automobile Manufacturers made such a request during the Tier 3 rulemaking. Meanwhile, the NRC recommended that "EPA and NHTSA should investigate the overall well-to-wheels CAFE and GHG effectiveness of increasing the minimum octane level and, if it is effective, ***determine how to implement an increase in the minimum octane level*** so that manufacturers would broadly offer engines with

[47] P. Machiele, EPA. May 5, 2015. "EPA's Regulatory Authority to Address Octane." Presentation to EPA Mobile Sources Technical Review Subcommittee.

significantly increased compression ratios for further reductions in fuel consumption."[48] Similarly, the attached Ricardo report states, "It is clear that implementing a high octane fuel standard would provide opportunity for increased engine efficiency and hence reduced greenhouse gases."

EPA clearly has the authority to regulate gasoline octane ratings, as octane has direct implications for emissions of CO_2 and other pollutants. EPA has acknowledged this authority, stating that "CAA 211(c) provides EPA with broad and general authority to regulate fuels and fuel additives; this authority could be used to…'control'…the octane level of gasoline."[49] While EPA has acknowledged it has the authority to regulate octane levels, the agency has suggested that the "time frame to complete all the steps [to implement octane regulations] could be ~10 years" and that "[e]ven if the rule were initiated now it would likely be a number of years before it could be implemented."[50] Chris Grundler, director of EPA's office of transportation and air quality, recently confirmed that EPA is not likely to consider regulating gasoline octane levels before 2025.[51]

Although RFA believes adoption of new regulations governing octane levels could be done relatively quickly (certainly more quickly than 10 years), EPA maintains that an extremely long lead time is required. Similarly, automakers would require a long planning horizon to adjust engineering and design activities in response to impending changes to fuel composition. Given the long lead time involved in effectuating changes to EPA regulations and automaker engineering and design plans, the agencies should indicate ***now*** the future direction of potential octane regulation and HOLC fuel introduction. That is, EPA and NHTSA should use the MTE process as an opportunity to respond to stakeholder outcry for HOLC fuels. The Proposed and Final Determinations should include the regulatory roadmap that the agencies, automakers and other stakeholders can follow to guarantee gasoline in 2025 and beyond has the necessary minimum octane rating to enable proliferation of advanced IC engine technologies that improve fuel efficiency and slash GHG emissions.

Attachments:

A: ***The Draft Technical Assessment Report: Implications for High Octane, Mid-Level Ethanol Blends*. Ricardo, Inc. September 20, 2016. Project Number C013713**

B: ***Summary of High-Octane, Mid-Level Ethanol Blends Study*. Oak Ridge National Laboratory. July 2016. ORNL/TM-2016/42**

C: ***Evaluation of Costs of EPA's 2022-2025 GHG Standards With High Octane Fuels and Optimized High Efficiency Engines*. AIR, Inc. September 16, 2016**

---

[48] NRC. June 2015, at 2-86.

[49] P. Machiele, EPA. May 5, 2015. "EPA's Regulatory Authority to Address Octane." Presentation to EPA Mobile Sources Technical Review Subcommittee.

[50] *Id*.

[51] Society of Automotive Engineers. Aug. 3, 2016. *GM, Honda execs agree: Higher octane gas needed to optimize ICE efficiency.* http://articles.sae.org/14940/

THE DRAFT TECHNICAL ASSESSMENT REPORT: IMPLICATIONS FOR HIGH OCTANE, MID-LEVEL ETHANOL BLENDS

FINAL REPORT

Prepared for:

Renewable Fuels Association
425 3rd Street
Washington DC, 20024

Prepared by:

Ricardo, Inc.
40000 Ricardo Dr.
Van Buren Twp., MI 48111

Ricardo Project Number:
C013713

Date Issued:
September 20, 2016

REVISION HISTORY

Revision	Date	Section #s Affected	Changes Made	Changed By
1	Sep 20, 2016	all	First issue	DLB2

EXECUTIVE SUMMARY

Ricardo, Inc. was retained by the Renewable Fuels Association to conduct a detailed analysis of the Draft Technical Assessment Report (TAR), which is the first step in the Midterm Evaluation of Light-duty Vehicle Standards for Model Years 2022-2025. A key objective of the analysis was to examine how and whether the TAR addresses fuels, and specifically whether it examines the potential use of high octane, mid-level ethanol blends (20-40% by volume) in optimized spark-ignition engines (e.g., high compression, turbocharged, downsized) to help OEMs achieve desired fuel economy and emissions standards. We also analyzed other literature to provide insight into the role that ethanol-based high octane fuels might play in facilitating increased fuel economy and reduced emissions under the federal standards.

Our analysis found that fuels—and ethanol, specifically—are rarely discussed in the TAR in the context of helping automakers meet fuel economy and emissions standards. However, the TAR does examine in detail a number of advanced spark-ignition engine technologies that would clearly produce greater fuel economy and emissions benefits when using higher octane mid-level ethanol blends than regular gasoline.

Ethanol has many beneficial properties when blended with gasoline for increasing the efficiency of spark-ignition engines. In a landmark automotive industry study, Stein, Polovina, Roth, et. al. showed that knock-limited performance can be increased by up to 5 times with a high octane ethanol blend in a DI turbocharged engine.[1] Significant performance increases such as this are the enablers for engine downsizing and compression ratio increases leading to efficiency improvements in future powertrain designs. The work went on to show that by redesigning the engine to take advantage of E30-100 RON fuel in an F150 pickup truck greenhouse gases could be reduced 6% on the EPA test cycles and an even more impressive 9% in real world driving conditions.[2]

Chow, Heywood and Speth[3] at MIT also examined the benefits of a higher octane standard gasoline for the U.S. light-duty vehicle fleet and found "ultimately by redesigning vehicles to take advantage of premium gasoline, fleet fuel consumption and GHG emissions can be reduced by 4.5-6.0% (for 98 RON-100 RON, respectively) over the baseline case." It is important to note that the Stein et al study found a greater benefit not due to the higher

[1] Stein, R., Polovina, D., Roth, K., Foster, M. et al., "Effect of Heat of Vaporization, Chemical Octane, and Sensitivity on Knock Limit for Ethanol - Gasoline Blends," SAE Int. J. Fuels Lubr. 5(2):2012, doi:10.4271/2012-01-1277.

[2] Leone, T., Olin, E., Anderson, J., Jung, H. et al., "Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO2 for a Turbocharged DI Engine," SAE Int. J. Fuels Lubr. 7(1):2014, doi:10.4271/2014-01-1228.

[3] Chow, E., Heywood, J., and Speth, R., "Benefits of a Higher Octane Standard Gasoline for the U.S. Light-Duty Vehicle Fleet," SAE Technical Paper 2014-01-1961, 2014, doi:10.4271/2014-01-1961.

octane rating of the fuel, but because of the greater charge cooling effect of ethanol over premium gasoline.

Recently, automotive industry executives have added their voices to the engineering and academic communities calling for higher octane fuels. According to Bob Lee, Senior VP of Powertrain at FCA, "We need to find a new equilibrium. Whether it is 98 or 100 octane, we need something at that level." Tony Ockelford, director of product and business strategy for Ford's powertrain operations added, "100 RON has been on the table for a long time, the only way we will ever get there is to continue to push and work in a collaborative way." [4] GM VP Dan Nicholson again spoke to this point at the 2016 CAR Management Briefing Seminars, saying, "higher octane fuels are the cheapest CO2 reduction on a well-to-wheels analysis. Fuels and engines must be designed as a total system." Robert Bienenfeld, American Honda AVP, agreed that the industry must push for a higher fuel-octane "floor" in the U.S.[5]

It is clear that implementing a high octane fuel standard would provide opportunity for increased engine efficiency and hence reduced greenhouse gases, and doing so by blending with ethanol provides an even greater benefit due to ethanol's high heat of vaporation combined with the inherently low carbon footprint of ethanol. Many of the technologies discussed in the Draft TAR, including ones with the highest expected penetration rates, could produce *greater* GHG and fuel economy benefits if paired with fuels offering higher octane ratings and an inherently higher charge cooling characteristic. For example, GDI, turbocharging, downsizing, cylinder deactivation and higher compression ratio NA engines are all technologies that are relied upon in the Draft TAR as examples of pathways to meeting the 2025 GHG and fuel economy standards and which could benefit further from high octane mid-level ethanol blends such as E30. Hence high octane mid-level ethanol can be thought of as a technology which improves the performance of other key technologies already in the TAR for reducing greenhouse gases, and it does so with minimal or no incremental cost increase to the vehicle.

In addition to the increased efficiency and reduced GHG emissions, ethanol could contribute to reducing the U.S. dependency on foreign oil and improving national energy security.

[4] Truett, R., "Powertrain executives press for higher octane gasoline to help meet mpg, CO2 rules," Automotive News, April 13, 2016.
[5] http://articles.sae.org/14940/

TABLE OF CONTENTS

THE DRAFT TECHNICAL ASSESSMENT REPORT: IMPLICATIONS FOR HIGH OCTANE, MID-LEVEL ETHANOL BLENDS

1 INTRODUCTION

The Renewable Fuels Association (RFA), the leading trade association for America's fuel ethanol industry, has requested a detailed analysis of the Draft Technical Assessment Report (TAR), which is the first step in the Midterm Evaluation (MTE) of Light-duty Vehicle Standards for Model Years (MY)2022-2025. This report is the result of the investigation completed to address the following objectives:

- How and whether the TAR addresses fuels, and specifically the potential for the use of high octane, mid-level ethanol blends (20-40% by volume) in optimized spark-ignition engines (e.g., high compression, turbo-charging, downsizing) to help OEMs achieve desired fuel economy and emissions standards?
- Whether the TAR presents opportunities to expand and/or expedite the use of high octane mid-level ethanol blends?
- Whether the technical assumptions and projections in the TAR regarding various automotive technologies and transportation fuels are consistent with industry expectations and other available information?
- Discussion of what additional information may need to be developed and provided to the U.S. Environmental Protection Agency (EPA), National Highway Traffic Safety Administration (NHTSA), and California Air Resources Board (CARB) to ensure the agencies properly address the potential role of ethanol-based high octane fuels in optimized engines as the Midterm Evaluation progresses
- Other issues that potentially impact fuel ethanol

The investigation included the following steps:

- Review and analyze TAR's treatment of alternative fuels and engine technologies that can benefit from high-octane and/or ethanol-containing fuels
- Compare assumptions and projections in the TAR with those of industry expectations
- Perform limited literature review on the effects of octane and ethanol fuel to increase engine efficiency
- State findings and conclusions in an objective, written report

2 OVERVIEW OF THE TAR

The U.S. EPA must determine, through the MTE whether the MY2022-2025 light-duty vehicle greenhouse gas (GHG) emissions standards, established in 2012 and known as the Final Rule-Making (FRM 2012), are still appropriate, given the latest available data and information. EPA's MTE process could result in one of three possible outcomes: the standards are deemed appropriate and remain in place, the standards should be made less stringent, or the standards should be made more stringent.

In the Draft TAR, EPA provides its initial technical assessment of the technologies available to meet the MY2022-2025 GHG standards and one reasonable compliance pathway, and NHTSA provides its initial assessment of technologies available to meet the augural MY2022-2025 Corporate Average Fuel Economy (CAFE) standards and a different reasonable compliance pathway. The agencies' independent analyses complement one another and reach similar conclusions:

- A wider range of technologies exist for manufacturers to use to meet the MY2022-2025 standards, and at costs that are similar to or lower than those projected in the 2012 rule;
- Advanced gasoline vehicle technologies will continue to be the predominant technologies, with modest levels of strong hybridization and very low levels of full electrification (plug-in vehicles) needed to meet the standards;
- The car/truck mix reflects updated consumer trends that are informed by a range of factors including economic growth, gasoline prices, and other macro-economic trends. However, as the standards were designed to yield improvements across the light duty vehicle fleet, irrespective of consumer choice, updated trends are fully accommodated by the footprint-based standards.

Additionally, while the Draft TAR analysis focuses on the MY2022-2025 standards, the agencies note that the auto industry, on average, is over-complying with the first several years of the National Program. The Draft TAR is organized as follows:

Chapter 1 introduces the National Program and lays out the Midterm Evaluation process and timeline.

Chapter 2 provides an overview of the agencies' approach as a collaborative, data-driven, and transparent process.

Chapter 3 summarizes recent trends in the Light-Duty vehicle fleet since the FRM 2012 with the key finding that auto manufacturers have over-complied with the GHG and CAFE standards program in the first three years, even in the face of record vehicle sales, a decline in the price of gasoline, and a rise in truck shares. Furthermore, it highlights technology

penetration rates with the increase of several gasoline engine and transmission technologies on track or ahead of the projections made in the 2012 FR and strong hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) at low levels of uptake.

Chapter 4 describes the baseline vehicle fleets and the reference fleet, which is the future fleet projection out to MY 2025; furthermore, it justifies the differences between EPA's and NHTSA's baseline fleets by stating that the combination of approaches strengthens the robustness of their results. Both fleets use the Energy Information Administration's Annual Energy Outlook 2015 (AEO 2015) along with IHS-Polk projections as the basis for total vehicle sales to 2025.

Chapter 5 gives an in-depth assessment of the state of vehicle technologies to improve vehicle fuel economy and reduce GHG emissions in terms of incremental cost and effectiveness as well as expected lead times for those technologies. One of the key findings is that there has been a "significant rate of progress made in automotive technologies over the past four years since the MY2017-2025 standards were established." In addition the agencies assess future technology developments expected through MY2025. Technologies that were considered in the 2012 FR are re-evaluated plus new technologies that have been introduced since the 2012 FR was written or are experiencing noticeable penetration when none had been anticipated, such as higher compression ratio engines or greater penetration of Continuously Variable Transmissions (CVTs). There are other technologies under development that are expected to be a part of the fleet mix before 2025 such as 48V mild hybrids. Chapter 5 alone comprises nearly half of the total Draft TAR volume at 588 out of 1217 pages and includes 615 references.

Chapter 6 reviews issues around consumer acceptance of fuel-saving and emission-reducing technologies and finds "that it is possible to implement these technologies without significant hidden costs." In other words, "the reduced operating costs from fuel savings over time are expected to far exceed the increase in up-front vehicle costs."

Chapter 7 discusses the effects of employment in the automotive sector, concluding that "the net effect of the standards on employment is likely to be small compared to macroeconomic and other factors affecting employment."

Chapter 8 assesses the estimated overall crash safety impacts of the MY2022-2025 standards which stem primarily from the weight reduction that is expected to be a part of meeting those standards. This is a critical piece of NHTSA's work as they are the nation's watchdog for vehicle safety as well as fuel economy.

Chapter 9 looks at the status of the infrastructure for alternative fueled vehicles, including flex fuel vehicles that may operate on high-ethanol blends such as E85. However, the "two

technologies the agencies believe will be important for achieving longer-term climate and energy goals [are] plug-in electric vehicles (PEVs) and fuel cell electric vehicles (FCEVs)." E85 and natural gas infrastructure is scarcely discussed in this chapter, as most of the focus is on electrical charging infrastructure. As concluded in the FRM 2012, EPA believes only "a very small percentage of PEVs" will be needed to meet the MY2025 standards, and "that infrastructure is progressing sufficiently."

Chapter 10 describes the economic and other inputs (such as real world fuel economy/GHG emissions gap [to test cycle numbers], vehicle miles traveled, energy security, the social cost of carbon emissions and others) used in the agencies' analyses.

Chapter 11 provides an overview of "a wide range of optional compliance flexibilities" offered by the national program to manufacturers to allow for consumer choice while spurring technology development, reducing compliance costs and achieving significant GHG and oil reductions.

Chapters 12 and 13 get to the bottom line and show the expected outcomes of the national program, namely the 2025 average light-duty vehicle fuel economy is expected to be 46.3 mpg actual or 50.8 mpg-equivalent (using only tailpipe improvements and no flexibilities) for a 52/48% car/truck mix and fuel prices as per the reference case from AEO 2015, and the CO_2 output is expected to be 175 g/mi. Table ES-1 from the executive summary (without footnotes) is reprinted here:

Table ES- 1 Projections for MY2025: Car/Truck Mix, CO2 Target Levels, and MPG-equivalent[1]

		AEO 2015 Fuel Price Case		
	2012 Final Rule	AEO Low	AEO Reference	AEO High
Car/truck mix	67/33%	48/52%	52/48%	62/38%
CAFE (mpg)[2]	48.7	45.7	46.3	47.7
CO_2 (g/mi)	163	178	175	169
MPG-e	54.5	50.0	50.8	52.6

The agencies reiterate again their position "that the MY2022-2025 standards can be achieved largely through the use of advanced gasoline vehicle technologies with modest penetrations of lower cost electrification (like 48 volt mild hybrids…) and low penetrations of higher cost electrification (like strong hybrids…)." The agencies also hint at the possibility that they are more likely to increase the stringency of the standards than not by noting that due to the rapid pace of innovation "the agencies may consider effectiveness and cost of additional technologies as new information… becomes available for further steps of the Midterm Evaluation."

Secondly, they conclude that average cost per vehicle of meeting the MY2025 standards is $894 - $1017 for EPA's analysis of the GHG program and $1245 for NHTSA's analysis of the

CAFE program, noting these are incremental costs beyond those incurred for meeting the MY2021 standards. For comparison, EPA's assessment in the 2012 FR was $1070, or $53 - $176 higher than the Draft TAR results now declare. This is another indication that the agencies may be leaning more towards increasing the stringency of the standards at the conclusion of the MTE.

Thirdly, EPA and NHTSA give their views as to possible penetration rates for select technologies needed to comply with the MY2025 standards in Table ES-3, reprinted here.

Table ES- 3 Selected Technology Penetrations to Meet MY2025 Standards[1]

	GHG	CAFE
Turbocharged and downsized gasoline engines	33%	54%
Higher compression ratio, naturally aspirated gasoline engines	44%	<1%
8 speed and other advanced transmissions[2]	90%	70%
Mass reduction	7%	6%
Stop-start	20%	38%
Mild Hybrid	18%	14%
Full Hybrid	<3%	14%
Plug-in hybrid electric vehicle[3]	<2%	<1%
Electric vehicle[3]	<3%	<2%

It is interesting to note that the biggest disparities (in terms of absolute percentages) are for turbocharged downsized engines and for high compression ratio naturally aspirated (NA) engines; however, both of these technologies are ones which would benefit from a meaningful increase in the octane rating of standard-grade gasoline fuels.

Fourthly, EPA analysis indicates a net lifetime consumer savings (incremental vehicle cost minus incremental fuel savings) of $1460 - $1620 with a 5-5½ year payback period; NHTSA analysis shows a potential savings of $680 per vehicle with a 6½ year payback.

Finally, the agencies project the societal benefits resulting from the National Program. The EPA estimates that the standards could reduce national GHG emissions by 540 million metric tons (MMT) and reduce oil consumption by 1.2 billion barrels over the lifetimes of MY 2021-2025 vehicles; NHTSA estimates a national GHG emissions reduction of 748 MMT and 1.6 billion barrels of oil saved under the augural MY2022-2025 CAFE standards for MY2016-2028 vehicles.

These GHG and oil consumption reductions would come at a cost to industry estimated as $34 - $38 billion, but result in consumer fuel savings of $89 billion. All told, the net societal benefits are projected at $90 - $94 billion according to primary EPA analysis. NHTSA comes

to a similar net benefit of $88 billion with its primary analysis but uses higher industry costs ($87 billion) to implement the vehicle program in MY2016-2028 and greater fuel savings ($120 billion).

3 THE TAR'S IMPLICATIONS FOR MOTOR FUELS

A major conclusion in the executive summary of the Draft TAR is that the agencies expect "advanced gasoline vehicle technologies will continue to be the predominant technologies … needed to meet the standards." By adding to that the statement "with modest levels of strong hybridization and very low levels of full electrification (plug-in vehicles)" they relegate alternative fuels in general to a very minor role. And in further stating that the "two technologies the agencies believe will be important for achieving longer-term climate and energy goals – plug-in electric vehicles (PEVs) and fuel cell electric vehicles (FCEVs)" they, to a large extent, dismiss any direct discussion around the benefits that high-octane mid-level ethanol blends could play in helping the country achieve these energy efficiency goals, not to mention helping to meet the goals of the Renewable Fuel Standard (RFS) program.

On the other hand, many of the technologies that are discussed in the Draft TAR, including the ones with the highest expected penetration rates, could produce *greater* GHG and fuel economy benefits if paired with fuels offering higher octane ratings than contemplated by EPA and NHTSA for the agencies' modeling exercises. Thus, the TAR implicitly makes a case for increased use of higher octane fuels, such as mid-level ethanol blends like E25 or E30. For example, gasoline direct injection (GDI) engines that are turbocharged and downsized are projected to be used in ⅓ - ½ of the vehicle fleet in MY2025[6], up from 18% in MY2015[7], and they offer a GHG benefit ranging from 10% to nearly 12%[8]. These downsized, boosted engines running on an E30 blend and having their compression ratios increased 3.0 units could gain an additional 6% in efficiency compared to running on today's E10 gasoline.[9]

Also note that in their benchmarking of the Mazda SkyActiv-G engine, the EPA used both 88 AKI LEV III E10 fuel as well as 93 AKI Tier 2 certification gasoline "to investigate if there was more efficiency to be gained from higher octane." Without making any further modifications

[6] Draft TAR, pES-10, Table ES-3
[7] Draft TAR, p5-19
[8] Draft TAR, p5-290, Table 5.64 depending on the vehicle application according to the latest analysis done for the MTE
[9] Leone et al in SAE 2014-01-1228 estimated a 6% CO2 emissions reduction on the fuel economy test cycle in an F150 pickup with the 3.5L EcoBoost engine at 13:1 compression ratio on E30 gasoline and a 9% reduction over the more aggressive US06 drive cycle.

to the engine or controls, they found up to a 3% gain in brake thermal efficiency by running on the higher octane fuel.[10]

In addressing the engine maps created for NHTSA's updated analysis in the TAR, NHTSA also noted that naturally-aspirated engines were calibrated on 87 AKI fuel while turbocharged engines were calibrated on 93 octane fuel. The fuel economy modeling results were later adjusted for differences in heating values between the fuels. [11]

Section 3 of this report highlights sections in the Draft TAR that describe the technologies (including engine, transmission and hybrid vehicles) that do have the potential for benefiting from using high octane mid-level ethanol blends.

3.1 Engines

3.1.1 GDI, Turbocharging, Downsizing, Cylinder Deactivation (TAR Sec 5.2.2.7)

These technologies are used to increase the average load on the engine, and therefore make it more prone to knocking. Because the engine tends to run more often at or near a knock-limited condition, it can take advantage of a high octane mid-level ethanol blend. Ethanol with its high octane rating, high sensitivity (S = RON – MON; where RON stands for research octane number and MON stands for motor octane number), and high heat of vaporization can be used in mid-level gasoline blends to further improve the efficiency of engines employing this technology most effectively by allowing their compression ratios to be raised. Ethanol allows for efficiency gains even if the compression ratio is not increased by allowing the spark timing to be advanced when operating under knock-limited conditions.[12]

GDI is the most rapidly expanding technology with market penetration going from 2.3% in MY2008 to over 45% in MY2015 as shown in Figure 1.[13] Figure 2 shows that the agencies expect its penetration to continue increasing out through MY2021 and into MY2025, and for the penetration of turbocharged, downsized engines to accelerate to the point that it matches GDI penetration by 2021. Turbocharged engines have also grown rapidly and the two are often employed together in a downsized engine package because the in-cylinder charge cooling effect from GDI helps to mitigate the knocking tendency. Cylinder Deactivation is used to disable some (usually ½) of the cylinders so that the active cylinders carry twice the load, and the control capability is evolving to the point where cylinders can be disabled on a cycle-by-cycle basis so that it can be applied to smaller engines and engines with an odd number of cylinders.

[10] See Figure 8 and discussion of Ellis et. al.
[11] TAR p5-504
[12] This is described in greater detail in section 5 of this report
[13] TAR p3-12

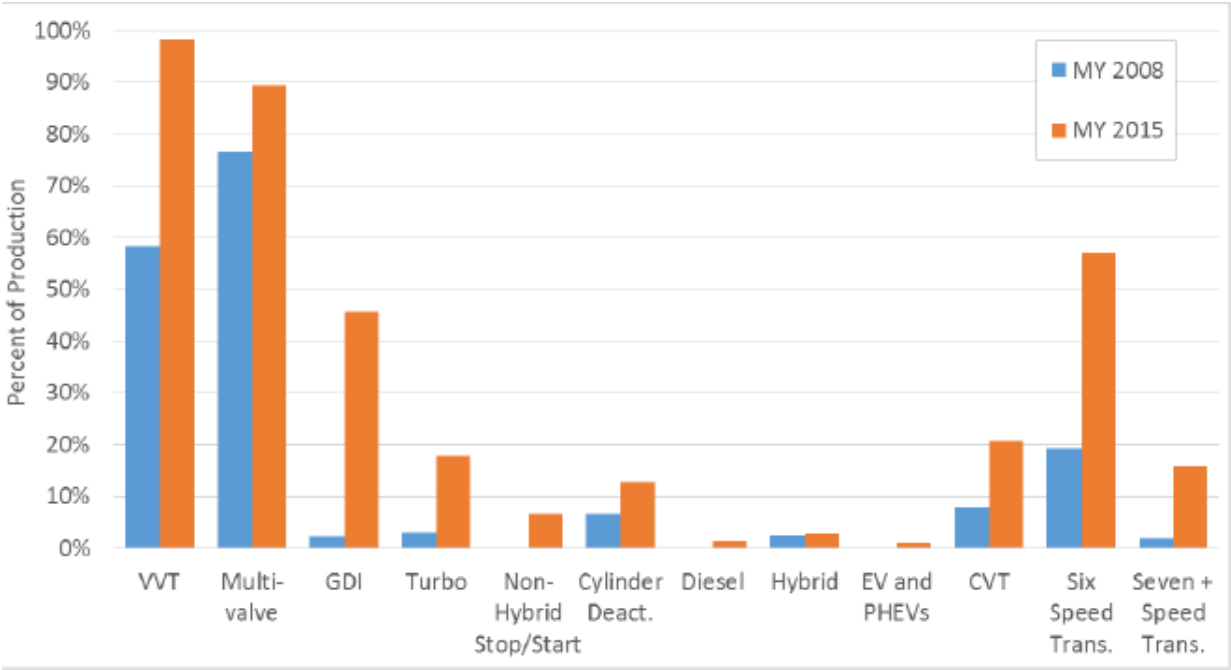
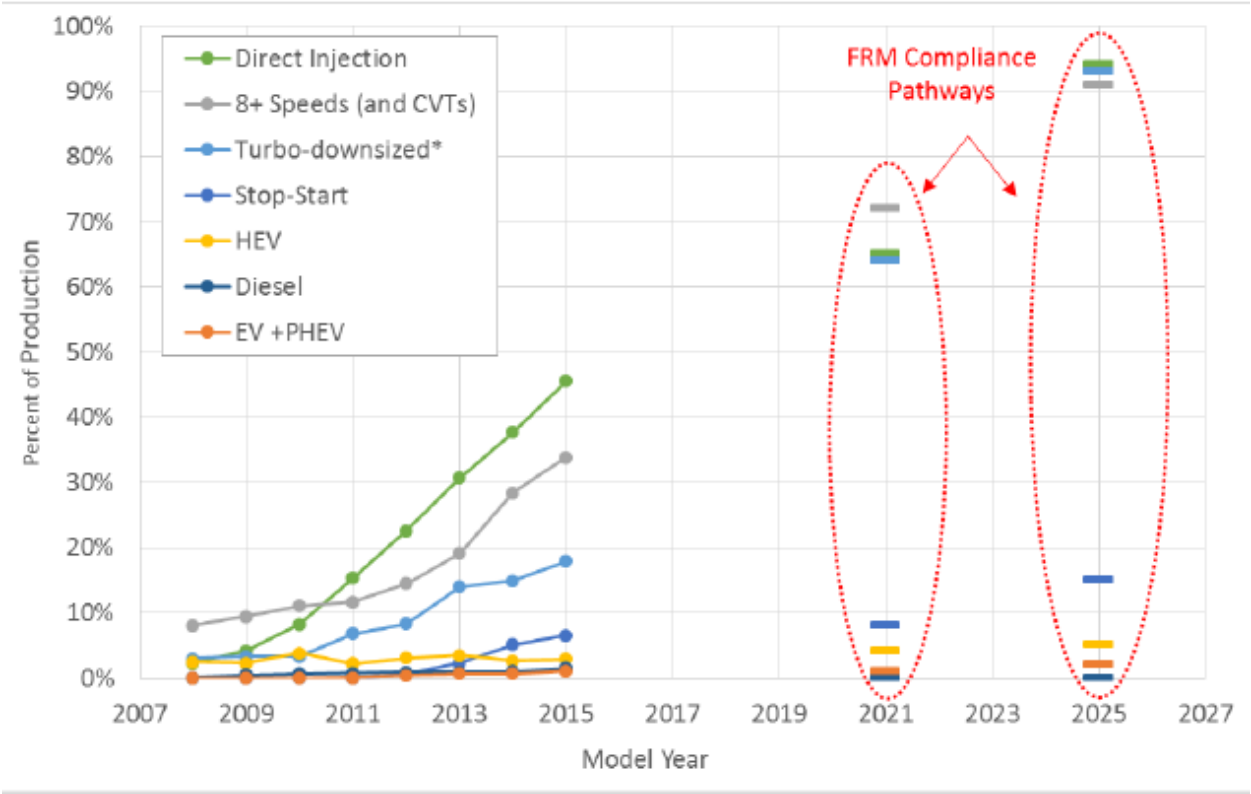


FIGURE 1 LIGHT DUTY VEHICLE TECHNOLOGY PENETRATION SHARE SINCE THE 2012 FINAL RULE (TAR FIGURE 3.10)



* Data through 2015 includes all turbocharged vehicles, not specifically turbo-downsized engines

FIGURE 2 TECHNOLOGY CHANGES SINCE MY2009 (TAR FIGURE 3.11)

3.1.2 Atkinson cycle (TAR Sec 5.2.2.9)

Atkinson cycle engines have increased geometric compression ratio and they use either very early or very late intake valve closure to effectuate a lower compression ratio and avoid knock while maintaining a high expansion ratio. "Prior to 2012, the use of naturally-aspirated Atkinson Cycle engines has been limited to HEV and PHEV applications where the electric machine could be used to boost torque output, particularly at low engine speeds…. Since 2012, Atkinson Cycle engines have been introduced into non-hybrid applications."[14] In the same way that high octane mid-level ethanol blends can be used to improve the efficiency of gasoline turbocharged direct injection (GTDI) engines it can be effectively used in Atkinson cycle engines.

3.1.3 Miller Cycle (TAR Sec 5.2.2.10)

In the TAR, Miller cycle is described essentially as a boosted Atkinson cycle.[15] VW has introduced Miller cycle engines in the EA888 engine for Audi vehicles and also the smaller EA211 TSI evo engine for VW vehicles in Europe first and then the US. Just as for Atkinson cycle engines, high octane mid-level ethanol blends can be used for further efficiency gains in Miller cycle engines. The agencies demonstrate that these technologies have already entered the market, stating that "As of MY2017, all of Mazda's engines for the U.S. market are either Atkinson Cycle or Miller Cycle (boosted Atkinson)."[16]

3.1.4 VCR & Other Longer Term Engine Technologies (TAR Sec 5.2.2.14)

Variable Compression Ratio (VCR) is a means to offer a range of compression ratios so that at lighter load conditions a high compression ratio can be used to effect efficiency gains, and at higher load conditions a low compression ratio can be used to avoid knock. Nissan recently announced its intention to produce a turbocharged engine with variable compression ratio,[17] as a signal coming well ahead of expectations in the TAR. While VCR technology would seemingly obviate the need for higher octane fuels, mid-level ethanol blends would still offer a benefit by allowing the engines to operate at high compression ratio more frequently and/or allowing the engine to be further downsized.

Also in this section of the TAR is tucked away mention of the DOE Co-Optimization of Fuels and Engines (Co-Optima) [18] program which holistically treats engines and the fuels they burn as an integrated system in order to improve the efficiency of motor vehicles and also to advance the use of renewable fuels such as high octane mid-level ethanol blends.

---

[14] TAR p5-31
[15] TAR pp5-33 & 5-34
[16] TAR p5-31
[17] http://www.autoblog.com/2016/08/14/infiniti-vc-t-engine-variable-compression-official/
[18] TAR pp5-41 & 5-42

3.2 Transmissions

3.2.1 Trans Shift Strategies and Torque Converter Lockup Strategy (TAR Sec's 5.2.3.10 & 5.2.3.11)

Transmissions have the ability to significantly impact vehicle efficiencies by changing the speed and load at which the engine operates. Transmissions with a greater number of gear ratios and CVT transmissions achieve fuel economy gains by causing the engine to operate in its peak efficiency region more frequently. By reducing the knocking tendency of engines at or near their peak efficiency regions, high octane mid-level ethanol blends can further increase the GHG and fuel economy benefits of vehicles utilizing improved transmission shift and torque convertor lockup strategies.

3.3 Hybrid Electric Vehicles

3.3.1 Mild, Strong, & Plug-in Hybrids (TAR Sec's 5.2.4.3.2, 5.2.4.3.3 & 5.2.4.3.4)

Hybrid Electric Vehicles (HEVs) improve vehicle fuel efficiency through several mechanisms such as the ability to recover kinetic energy that would otherwise be lost (i.e. regen braking), which gives many hybrid vehicles their characteristic higher fuel economy on the 'city' FTP drive cycle than the 'highway' HFET. All hybrid vehicles (when operating on engine power for PEVs) and 'strong' HEVs especially operate more frequently at the engine's peak efficiency region, and for this reason would be able to capitalize on high octane mid-level ethanol blends' capability for further improving the efficiency and fuel economy and reducing GHG emissions. Hybrids that utilize Atkinson cycle engines are also subject to the potential gains from high-octane ethanol blends.

4 WHAT THE INDUSTRY IS SAYING ABOUT HIGH OCTANE FUELS

One area that leadership of the OEMs has started addressing publicly is that of calling for a higher octane fuel standard, as discussed in detail in Sec. 5.4 of this report. In a panel discussion at the 2016 SAE World Congress powertrain executives said they need higher octane gasoline … to meet the government's strict 2025 fuel economy and CO2 standards.[19] According to Bob Lee, Senior VP of Powertrain at FCA, "We need to find a new equilibrium. Whether it is 98 or 100 octane, we need something at that level." Tony Ockelford, director of product and business strategy for Ford's powertrain operations added, "100 RON has been on the table for a long time, the only way we will ever get there is to continue to push and work in a collaborative way." In August 2016, GM VP Dan Nicholson again spoke to this point at the 2016 CAR Management Briefing Seminars, saying, "higher octane fuels are the

[19] Truett, R., "Powertrain executives press for higher octane gasoline to help meet mpg, CO2 rules," Automotive News, April 13, 2016

cheapest CO2 reduction on a well-to-wheels analysis. Fuels and engines must be designed as a total system." Robert Bienenfeld, American Honda AVP, agreed that the industry must push for a higher fuel-octane "floor" in the U.S.[20]

5 Other Works Addressing Ethanol's Potential Role in High Octane Fuels

In this section we will first of all quantify the efficiency gains that can be had from increasing compression ratio, also explaining why compression ratios cannot be increased with existing engine technologies using our current standard gasoline octane ratings and even more so with engine technologies that are expected to be increasingly utilized in the future, such as downsizing and boosting. We will also explain the role of Direct Injection (DI) in allowing compression ratios to be increased while maintaining, or even increasing, the power and torque output of an engine, and the interaction with the fuel characteristics, namely its Heat of Vaporization (HoV) and sensitivity. Finally, we will look at the impact that high octane, mid-level ethanol blends can have on fuel economy and CO_2 reduction.

5.1 Effect of Compression Ratio on Efficiency

Compression ratio (CR) is fundamentally the key variable engine designers have to play with for impacting efficiency as we learn from the equation for an ideal gas thermodynamic cycle:

$$\eta = 1 - \frac{1}{CR^{\gamma-1}}$$

Where η is the efficiency of the cycle and γ is the ratio of specific heats of the working fluid. This equation teaches that increasing CR will continually increase efficiency forever; however, there are practical limits in applying this ideal equation to real engines, foremost of which is the tendency of a spark-ignition engine to knock.

The tendency to knock can be minimized by numerous engine design choices and control strategies, but is also critically impacted by the octane rating or the *anti-knock index* (AKI) of the fuel. The AKI rating of a fuel comes from the two primary octane ratings, RON and MON, which are measurements of a fuels knocking tendency in engines running under different conditions. One of the most important differences in the conditions is the location of the fuel injection and the amount of heating and vaporization it undergoes before entering the cylinder. This is important because today's modern high-efficiency engines often employ direct injection which experiences no heating and vaporization before entering the cylinder, so understanding the differences between the RON test and the MON test allows one to better

[20] http://articles.sae.org/14940/

project a fuel's anti-knock qualities for DI engines. This difference is expressed as the sensitivity of a fuel:

$$S = RON - MON$$

Studies have shown that the RON test more closely represents the conditions found in today's boosted, DI engines, and in fact since the air is preheated and the fuel injected far upstream in the MON test, the MON rating is actually a counter-indication of knocking tendency in boosted DI engines. In other words, a fuel's RON plus its sensitivity gives a better indication of knocking tendency. According to Kalghatgi et. al. "the true anti-knock quality of a gasoline is best described by an Octane Index, OI… which is defined as OI = (1-K)*RON + K*MON = RON – K*S… [where] downsized turbocharged engines of the next generation have negative values of K."[21]

Smith, Heywood and Cheng at MIT have stated: "The type of fuel chosen can have a profound impact on knock suppression through its beneficial chemical characteristics and the compounding impact of its evaporation with direct injection. High octane gasoline and alcohol fuels have been proven to reduce the propensity to knock due to their molecular structure…. In addition alcohol-based fuels have a higher heat of vaporization than traditional gasoline fuels, resulting in even lower charge temperatures, further reducing the probability of knock."[22]

Recognizing not only the importance of a fuel's 'chemical' octane rating as expressed by its RON and its sensitivity, but also a fuel's heat of vaporization to further reduce the propensity to knock in DI engines, Smith, Heywood and Cheng surveyed recent technical papers covering a "broad range of engine designs at a wide range of operating conditions" to determine the impact that CR has on efficiency; a summary of their results is shown below in Figure 3.

[21] Kalghatgi, G., Head, R., Chang, J., Viollet, Y. et al., "An Alternative Method Based on Toluene/n-Heptane Surrogate Fuels for Rating the Anti-Knock Quality of Practical Gasolines," SAE Int. J. Fuels Lubr. 7(3):2014, doi:10.4271/2014-01-2609.

[22] Smith, P., Heywood, J., and Cheng, W., "Effects of Compression Ratio on Spark-Ignited Engine Efficiency," SAE Technical Paper 2014-01-2599, 2014, doi:10.4271/2014-01-2599.

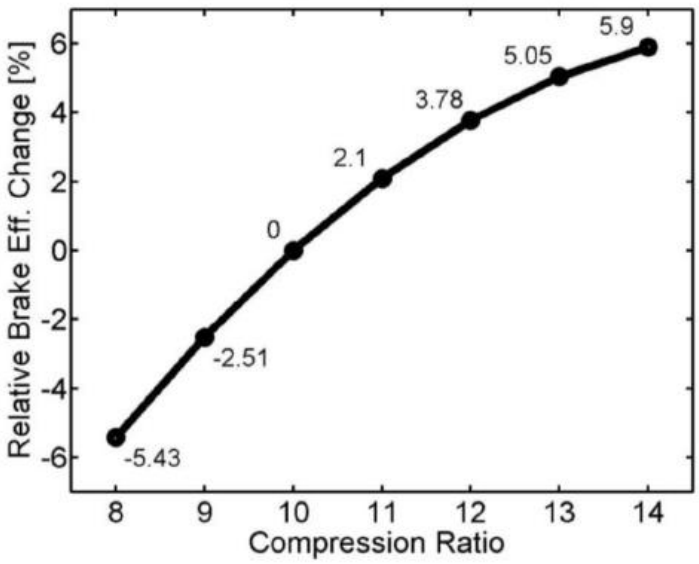


FIGURE 3 AVERAGE RELATIVE BRAKE EFFICIENCY CHANGE VERSUS COMPRESSION RATIO FOR ALL DATA SETS WITH RELATIVE VALUES FROM UNIT CHANGES IN COMPRESSION RATIO LABELLED.[23]

What is important to note is that increasing compression ratio can be expected to increase brake thermal efficiency of an SI engine but does so with ever diminishing gains.

5.2 Effect of Heat of Vaporization, Chemical Octane and Sensitivity

A landmark paper by Stein et. al. carefully examined and delineated the effects of chemical octane, heat of vaporization, and sensitivity of ethanol-gasoline blends on knock in a modern boosted DI engine.[24] First, the chemical effect was cleanly separated from the heat of vaporization, or "charge cooling" effect, by comparing performance of a neat gasoline (E0) with an E50 blend made from the same 88 RON gasoline blendstock using an upstream fuel injection (UFI) system. Secondly, the paper compared performance of the E50 blend injected upstream and completely vaporized with the UFI system against performance of the E50 blend directly injected into the cylinder (DI) where all of the vaporization occurs in the cylinder. Figure 4[25] below shows that at equal *knock-limited* combustion phasing (illustrated for example by the black arrows at 16 deg aTDC CA50 timing) the maximum achievable normalized torque output (represented on the x-axis as NMEP or net mean effective pressure) increases from 5 bar NMEP to 15 bar solely due to the chemical octane increase of the E50 blend over the E0 gasoline. The second black arrow points out the increased charge cooling effect results from ethanol's higher HoV and sensitivity when it is injected directly

[23] Taken from Figure 6 of Smith et. al.
[24] Stein, R., Polovina, D., Roth, K., Foster, M. et al., "Effect of Heat of Vaporization, Chemical Octane, and Sensitivity on Knock Limit for Ethanol - Gasoline Blends," SAE Int. J. Fuels Lubr. 5(2):2012, doi:10.4271/2012-01-1277.
[25] Taken from Figure 13 of Stein et. al.

into the cylinder; for contrast the UFI – DI difference for E0 gasoline is virtually non-existent as shown by the green and light grey lines. While the absolute values of the chemical and charge cooling effects vary with CA50 timing, it is noted that they are similar in magnitude for an E50 blend.

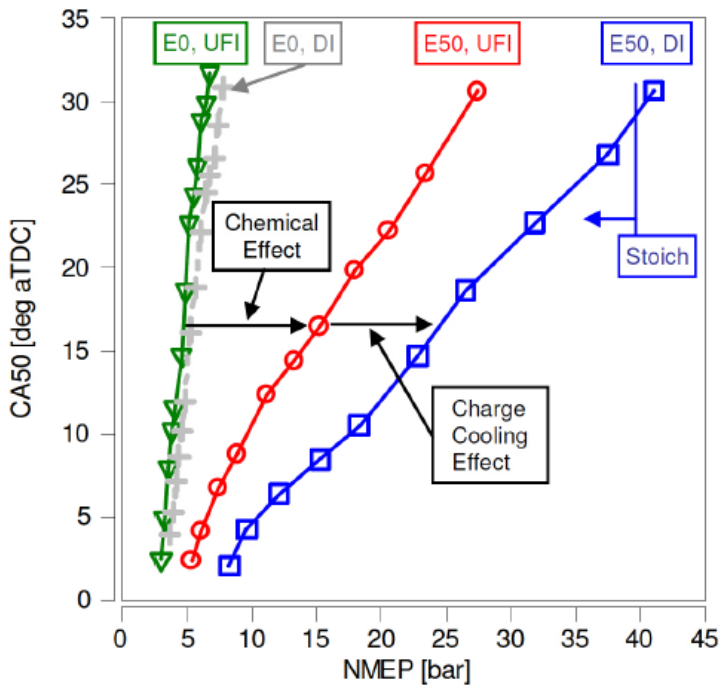


FIGURE 4 SEPARATION OF CHEMICAL OCTANE AND CHAGE COOLING EFFECTS ON KNOCK LIMIT FOR B88E5—R105 AT 10:1 CR AND 1500 RPM.

Importantly, but not surprisingly, the paper conclusively demonstrates that blending lower octane gasoline with ethanol to produce finished fuels with equivalent low RON is of no benefit in extending the knock-limited torque or NMEP of an SI engine.[26] The message here is that greater efficiency gains can be obtained by increasing the octane ratings of finished fuels by blending in ethanol rather than using ethanol to allow a drop in the RON of the gasoline blendstock. Even greater gains can be realized from a high octane ethanol blend over a neat gasoline with equivalent RON as was shown for the 97 and 99 RON fuel series.[27]

These experiments clearly reveal the mechanisms by which engines can achieve significantly enhanced torque levels using high octane ethanol blends, thereby laying the foundation stones for further efficiency gains to technologies such as GDI, turbocharging, downsizing and cylinder deactivation that are at the heart of the technology pathways used for attaining

[26] Stein et. al. show in Figure 23 that low octane fuels such as regular pump grade gasoline with a RON of 93 exhibit similar knock-limited performance for the tested E0, E10 and E20 blends.
[27] Figures 21 and 22 of Stein et. al. show higher octane blends give improved performance due to the charge cooling effect with higher ethanol levels of E10, E20 and E30.

the CO_2 reductions and FE improvements expected in the TAR. Efficiency gains from ethanol blends can be expected for current GDI boosted downsized engines (via less spark retard at moderate loads and less enrichment at high loads), and even greater efficiency gains are to be expected with future engines employing a greater degree of downsizing and technologies such as DI Atkinson cycle and Miller cycle, by taking advantage of the higher torque output capability that is enabled by ethanol blends.

5.3 Fuel Economy and CO_2 Benefits from High Octane Mid-Level Ethanol Blends

Further work was performed using the same combustion system developed above. This time, however, a 3.5L V6 Ford EcoBoost gasoline turbocharged engine was used and the engine dynamometer data was modeled in an F150 pickup truck to quantify the vehicle fuel economy gains and CO_2 reductions made possible with splash-blended ethanol-gasoline mixtures.[28] Engine performance was compared for regular-grade E10 fuel having measured values for AKI of 87 and RON of 91, E20 with 96 RON (AKI = 91), and E30 with 101 RON (AKI = 94) on the production engine at 10:1 CR and with the engine modified to 11.9:1 CR. The engine dynamometer data indicated efficiency gains of 4-5% for a 10% increment of ethanol splash blended in the base blendstock, which allowed for a CR increase of 1.9 units at equivalent output capability.[29]

Detailed vehicle simulation of an F150 pickup showed that a 4.8% reduction in CO_2 emissions was possible on the combined EPA metro and highway test cycles; similar results were obtained for the more aggressive US06 drive cycle.[30] Furthermore, since range between fill-ups is an important customer satisfaction index, and E20 has roughly 4% lower energy density than E10 on a per-gallon basis, miles-per-gallon fuel economy was calculated for the fuel/engine combinations above. As expected, range projections for E20 fuel and 11.9 CR came out equal or slightly better than E10 fuel at 10:1 CR.[31]

A second paper published the results from testing an E30 ethanol fuel blend in the same engine but with CR set to 13:1 and projecting fuel economy in the same F150 pickup truck but with the new engine/fuel test results.[32] The E30 blend had measured RON of 101 and

[28] Jung, H., Leone, T., Shelby, M., Anderson, J. et al., "Fuel Economy and CO2 Emissions of Ethanol-Gasoline Blends in a Turbocharged DI Engine," SAE Int. J. Engines 6(1):2013, doi:10.4271/2013-01-1321.
[29] See Figure 12 and the Summary/Conclusions of Jung et. al.
[30] See Figure 15 of Jung et. al.
[31] See Figure 16 of Jung et. al.
[32] Leone, T., Olin, E., Anderson, J., Jung, H. et al., "Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO2 for a Turbocharged DI Engine," SAE Int. J. Fuels Lubr. 7(1):2014, doi:10.4271/2014-01-1228.

AKI of 94 which allowed the CR of the engine to be increased to 13:1 while maintaining equivalent full load performance as the baseline engine at 10:1 burning the baseline E10 fuel.

Vehicle simulation of the F150 pickup showed that a 6% improvement in CO2 emissions on the CAFE fuel economy test was enabled by the high octane E30 blend and a more impressive 9% gain on the US06 drive cycle which is better at representing the real world behavior of typical drivers in the US.[33] In the real world driving scenario, vehicle range was again similar or better than on E10 even though E30's volumetric energy density is down by almost 8%.[34]

5.4 Impact of Higher Octane Rating and Ethanol Content on U.S. Fuel Economy and CO_2 Emissions

Chow, Heywood and Speth at MIT also examined the benefits of a higher octane standard gasoline for the U.S. light-duty vehicle fleet and found "ultimately by redesigning vehicles to take advantage of premium gasoline, fleet fuel consumption and GHG emissions can be reduced by 4.5-6.0% (for 98 RON-100 RON, respectively) over the baseline case, where no additional higher-octane vehicles are introduced."[35]

The effect of compression ratio, fuel octane rating, and ethanol content on spark-ignition engine efficiency was studied and published in the peer-reviewed journal "Environmental Science & Technology" a critical review article authored by scientists and engineers from Ford, GM, and FCA who are recognized world-wide for their expertise in the interaction of engines and fuels.[36] They found that higher octane ratings for regular-grade gasoline are an enabler for higher compression ratio, downsizing, turbocharging, downspeeding, and hybridization technologies and that "increasing compression ratios for future SI engines would be the primary response to a significant increase in fuel octane ratings." Furthermore stating, "higher ethanol content is one available option for increasing the octane ratings of gasoline and would provide additional engine efficiency benefits for part and full load operation," as shown in Figure 5.

[33] See Figure 22 of Leone et. al.
[34] See Figure 23 of Leone et. al.
[35] Chow, E., Heywood, J., and Speth, R., "Benefits of a Higher Octane Standard Gasoline for the U.S. Light-Duty Vehicle Fleet," SAE Technical Paper 2014-01-1961, 2014, doi:10.4271/2014-01-1961.
[36] Leone, T., Anderson, J., Davis, R., Iqbal, A., Reese, R., Shelby, M., Studzinski, W., "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency," Environ. Sci. Technol. 49, 10778–10789 (2015) doi:10.1021/acs.est5b01420.

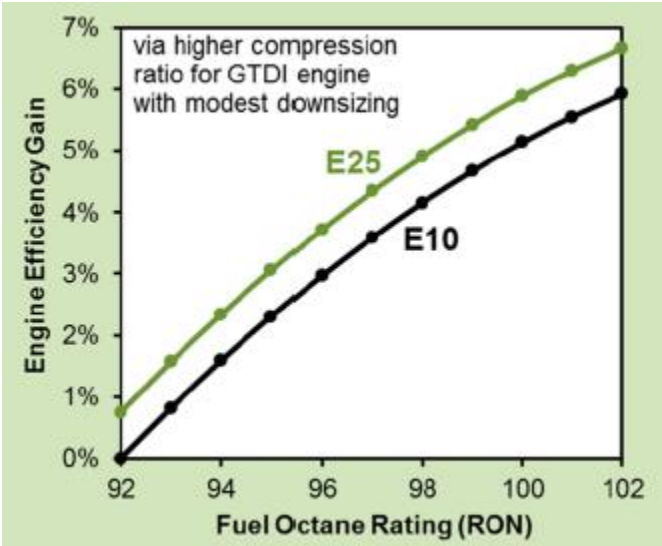


FIGURE 5 ENGINE EFFICIENCY GAINS FROM INCREASING FUEL OCTANE RATING THROUGH ETHANOL CONTENT AND COMPRESSION RATIO INCREASES FOR A GTDI ENGINE WITH MODEST DOWNSIZING.[37]

In addition to technical experts from the industry and academia defining the benefits available from high octane mid-level ethanol blends, SAE has noted that auto industry executives are also making public statements regarding the engine efficiency benefits.[38] GM and Honda executives said that raising the octane level of pump gasoline in the U.S. is integral to optimizing advanced combustion engine now in development. At the 2016 CAR Management Briefing Seminars Dan Nicholson, VP of Global Propulsion Systems at GM, said, "higher octane fuels are the cheapest CO2 reduction on a well-to-wheels analysis. Fuels and engines must be designed as a total system." Robert Bienenfeld, Assistant VP of Environment and Energy Strategy at American Honda agreed the industry must push for a higher fuel-octane floor in the U.S. prompting positive comments from EPA Director Chris Grundler. Although fuel changes are not part of the TAR, Grundler noted that the EPA is participating in the U.S. Dept. of Energy's Co-Optima program and has a group working on gasoline octane levels of future fuels. The TAR itself in fact notes that the aim of the Co-Optima program is to improve the *near-term* efficiency of engines.[39]

5.5 DOE's Summary of High-Octane, Mid-Level Ethanol Blends Study

Going beyond, and intermingled with, the Co-Optima initiative, the DOE has recently published a summary of its efforts investigating the potential of High Octane Fuel (HOF) with 25-40% ethanol blends.[40] DOE investigators came together from Oak Ridge National

[37] Taken from Leone, Anderson, Davis, et. al.
[38] http://articles.sae.org/14940/
[39] TAR p5-41
[40] Theiss, T., Alleman, T., Brooker, A., Elgowainy, A., Fioroni, G., Han, J., Huff, S., Johnson, C., Kass, M., Leiby, P., Uria Martinez, R., McCormick, R., Moriarty, K., Newes, E., Oladosu, G., Szybist, J., Thomas, J., Wang, M., West, B., "Summary of High-Octane, Mid-Level Ethanol Blends Study," ORNL/TM-2016/42, July 2016.

Laboratory, National Renewable Energy Laboratory, and Argonne National Laboratory with the objective of providing a quantitative picture of the barriers to adoption of HOF and the highly efficient vehicles it enables, and to quantify the potential environmental and economic benefits of the technology. Their findings are aligned with and reinforce the findings already noted by the industry and academic scholars above, specifically that the experimental and analytical results of this study considered together show that HOF mid-level ethanol blends could offer significant benefits for the United States. These benefits include a 5-10% efficiency increase in vehicles designed for increased ethanol content and a miles-per-gallon fuel economy parity with E10.

Furthermore, dedicated HOF vehicles exhibit nearly 15% lower well-to-wheels GHG emissions resulting from increased vehicle efficiency and corn ethanol production and use; future corn stover use shows potential to increase the well-to-wheels (WtW) savings to around 30%, Figure 6. By increasing the percentage of ethanol in the fuel supply, the amount of gasoline consumed decreases, thereby further reducing the nation's dependency on crude oil imports and enhancing U.S. energy security.

Available at http://info.ornl.gov/sites/publications/Files/Pub61169.pdf

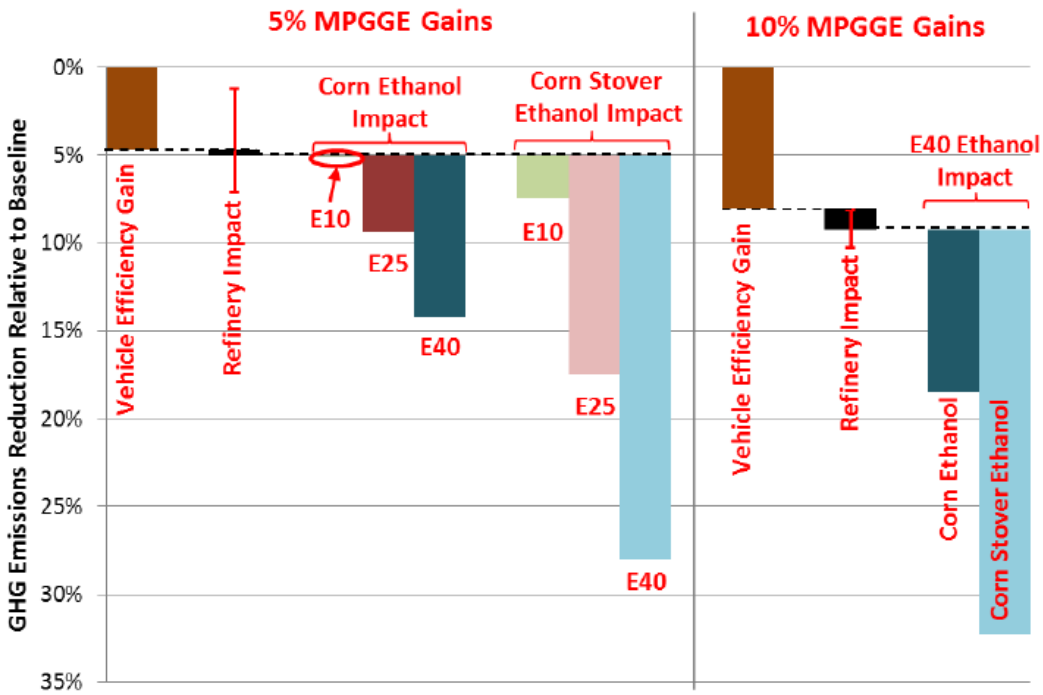


FIGURE 6 WTW GHG EMISSIONS REDUCTIONS IN VEHICLES FUELD BY HOFS WITH DIFFERENT ETHANOL BLENDING LEVELS RELATIVE TO REGULAR GASOLINE (E10) BASELINE VEHICLES.[41]

5.6 Summary of High Octane Ethanol Fuel Benefits

It is clear from the discussion above that increasing the compression ratio of new engine designs can be the primary means for taking full advantage of the ethanol's beneficial properties for increasing efficiency; namely ethanol's higher octane, higher sensitivity to autoignition kinetics, and higher heat of vaporization. This applies to DI engines especially, both NA and turbocharged, which are expected to comprise the majority of future engines for both conventional and hybrid vehicles. Secondly, the studies above also demonstrate that the gains available from a high octane mid-level ethanol fuel standard are greater in real world driving than the legislated drive cycles. Since the costs to an OEM for increasing compression ratio are minimal for a new engine design, it is clear that implementing a high octane mid-level ethanol fuel standard would be the lowest cost technology and have even greater benefits in real world driving.

6 Other Issues Impacting Increased Ethanol Use

The other key issue surrounding increased ethanol use in the U.S. is protecting equipment (both legacy fleet and new power or recreational equipment) that was not designed to operate on gasolines having more than a minimal level of ethanol. While the ORNL summary

[41] Figure 8 of Theiss et. al.

report[42] considers both the technical and commercial aspects of changing the nation's fuel supply infrastructure as viewed by four key stakeholder groups, we will briefly mention here what seems to be a pragmatic approach to switching over to high octane mid-level ethanol blends. That is simply a 2-nozzle pump distribution system.

In a 2-nozzle system the current standard gasoline fuel nozzle would be maintained and would protect legacy equipment and manufacturers that have not transitioned yet to the new mid-level ethanol fuel grade that new vehicles would have the option of benefiting from. To ensure that the new optimized vehicles will get only the higher octane mid-level ethanol blend a unique nozzle configuration can be employed such that old vehicles cannot get the new mid-level ethanol fuel and new vehicles cannot take the old E0 or E10 gasolines.

The ORNL report has shown that all the underground fuel supply equipment is capable of handling higher ethanol blends so only the above ground fuel dispensing equipment would need to change. That level of change would come at a relatively modest cost, much less than the cost of all the on-vehicle technology that would be needed to overcome the continued reliance on lower octane E10 gasoline.

[42] See Thiess et. al.

ORNL/TM-2016/42

Summary of High-Octane, Mid-Level Ethanol Blends Study

July 2016

Approved for public release.

Distribution is unlimited.

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2016/42

Bioenergy Technologies Program

Summary of High-Octane Mid-Level Ethanol Blends Study

Tim Theiss, ORNL
Teresa Alleman, NREL
Aaron Brooker, NREL
Amgad Elgowainy, ANL
Gina Fioroni, NREL
Jeongwoo Han, ANL
Shean Huff, ORNL
Caley Johnson, NREL
Mike Kass, ORNL
Paul Leiby, ORNL
Rocio Uria Martinez, ORNL
Robert McCormick, NREL
Kristi Moriarty, NREL
Emily Newes, NREL
Gdadebo Oladosu, ORNL
James Szybist, ORNL
John Thomas, ORNL
Michael Wang, ANL
Brian West, ORNL

Date Published: July 2016

Prepared by
OAK RIDGE NATIONAL LABORATORY (ORNL),
NATIONAL RENEWABLE ENERGY LABORATORY (NREL), and
ARGONNE NATIONAL LABORATORY (ANL)

Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

Page

LIST OF FIGURES

ACKNOWLEDGEMENTS

This report and the work described were sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE's) Bioenergy Technologies Office. The authors gratefully acknowledge the support and direction of Alicia Lindauer of that office. This work has also benefited from input, direction, and support from numerous peers within industry, the DOE Vehicle Technologies Office, and the U.S. Environmental Protection Agency. The authors also acknowledge and appreciate the thorough review from Scott Sluder at ORNL.

The authors are indebted to many technical experts in industry and government. While these experts provided valuable guidance and information as noted above, this consultation does not constitute endorsement by their organizations of either the study or the results.

ACRONYMS

ADOPT	Automotive Deployment Options Projection Tool
AKI	anti-knock index
ANL	Argonne National Laboratory
BOB	blendstock for oxygenate blending
CO_2e	GHG equivalent emissions deemed as CO_2 and often in mass units
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
E0	gasoline with no ethanol content
E10	gasoline with 10% ethanol
E85	also known as flex fuel, gasoline blended with 51-83% ethanol
Ex	other ethanol/gasoline mixtures with x% ethanol, such as E15, E25, E30, E40, E50
ETW	equivalent test weight
FFV	flexible-fuel vehicle
GHG	greenhouse gas
GM	General Motors Company
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
HFET	Highway Fuel Economy Test
HOF	high octane fuel
KLSA	knock limited spark advance
LP	linear programming
MON	motor octane number
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
RVP	Reid vapor pressure
RFS	Renewable Fuel Standard
RON	research octane number
SI	spark ignition
SUV	sport utility vehicle
UST	underground storage tank
US06	EPA US06 high-load, high-speed aggressive test cycle, part of the EPA Supplemental Federal Test Procedure (SFTP)
V6	V-six engine cylinder configuration
V8	V-eight engine cylinder configuration
WTW	well-to-wheels

BACKGROUND

Original equipment manufacturers (OEMs) of light-duty vehicles are pursuing a broad portfolio of technologies to reduce CO_2 emissions and improve fuel economy. Central to this effort is higher efficiency spark ignition (SI) engines, including technologies reliant on higher compression ratios and fuels with improved anti-knock properties, such as gasoline with significantly increased octane numbers. Ethanol has an inherently high octane number and would be an ideal octane booster for lower-octane petroleum blendstocks. In fact, recently published data from Department of Energy (DOE) national laboratories (Splitter and Szybist, 2014a, 2014b; Szybist, 2010; Szybist and West, 2013) and OEMs (Anderson, 2013) and discussions with the U.S. Environmental Protection Agency (EPA) suggest the potential of a new high octane fuel (HOF) with 25–40 vol % of ethanol to assist in reaching Renewable Fuel Standard (RFS2) and greenhouse gas (GHG) emissions goals. This mid-level ethanol content fuel, with a research octane number (RON) of about 100, appears to enable efficiency improvements in a suitably calibrated and designed engine/vehicle system that are sufficient to offset its lower energy density (Jung, 2013; Thomas, et al, 2015). This efficiency improvement would offset the tank mileage (range) loss typically seen for ethanol blends in conventional gasoline and flexible-fuel vehicles (FFVs). The prospects for such a fuel are additionally attractive because it can be used legally in over 18 million FFVs currently on the road. Thus the legacy FFV fleet can serve as a bridge by providing a market for the new fuel immediately, so that future vehicles will have improved efficiency as the new fuel becomes widespread. In this way, HOF can simultaneously help improve fuel economy while expanding the ethanol market in the United States via a growing market for an ethanol blend higher than E10.

The DOE Bioenergy Technologies Office initiated a collaborative research program between Oak Ridge National Laboratory (ORNL), the National Renewable Energy Laboratory (NREL), and Argonne National Laboratory (ANL) to investigate HOF in late 2013. The program objective was to provide a quantitative picture of the barriers to adoption of HOF and the highly efficient vehicles it enables, and to quantify the potential environmental and economic benefits of the technology. The project consisted of the following interconnected efforts.

- Develop a preliminary description of the key knock resistance properties of HOF to obtain a full understanding of both regulatory and ASTM standard development issues with regard to defining and introducing this fuel.

- Experimentally validate and measure the efficiency and performance benefits of HOF in a dedicated vehicle. This vehicle-level demonstration complements ongoing engine-based studies researching the benefits of increased fuel octane and engine compression ratio.

- Experimentally validate and measure the performance benefits of HOF in current FFVs. Demonstrating a performance benefit in legacy FFVs could help in marketing ethanol blends for the legacy FFV fleet, which could bolster development of the infrastructure for fueling future vehicles specifically designed for this fuel.

- Study the impacts on the petroleum refining sector and life-cycle GHG benefits across the US economy that would occur through broad adoption of HOF and the highly efficient vehicles it will enable. This effort is supported by analysis results under other subtasks:

  – Ascertain the shares of HOF and non-HOF demand of the light-duty vehicle fleet. These shares determine the refinery operations and the gasoline components in the refinery linear programming (LP) models.

- Define fuel property requirements for HOF. These constrain the properties of the hydrocarbon blendstock, which can have a large effect on life-cycle energy use and GHG emissions.

- Gain a broad understanding of economic and regulatory barriers to adoption of HOF by four key stakeholder groups: fuel producers/distributors, fuel retailers, vehicle manufacturers, and consumers. Each group is subject to different federal and state regulatory requirements and has different economic constraints.

- Determine the extent to which existing station and terminal infrastructure is compatible with HOF-range (25 to 40%) ethanol blends, whether infrastructure components are compatible, and whether there is a blend-level breakpoint at which infrastructure compatibility is less of an obstacle.

- Evaluate the cost reduction potential of HOF blendstocks including natural gasoline which has been suggested as a possible low-cost blendstock for HOF.

ENGINES AND KNOCK

A major efficiency-limiting combustion phenomenon in SI engines is referred to as knock or more specifically end-gas knock. Desired cylinder combustion events are initiated at the proper time by the spark which ignites the surrounding air-fuel mixture. A flame zone then expands, propagating through the combustion chamber, ideally consuming all the fuel, releasing heat and causing a pressure rise that imparts force on the moving piston. Most of the force increase is applied to the piston during the expansion stroke such that the combustion process creates useful mechanical work. As the spark-initiated flame zone expands, the unburned mixture beyond the flame zone is increasing in temperature and pressure due both to the expanding gas in the flame zone and the piston compressing the mixture further. Knock occurs when this unburned fuel-air mixture, known as the end-gas, detonates, or burns very rapidly essentially by compression ignition. This undesirable event is also referred to as autoignition of the air-fuel mixture. A knock event applies sudden forceful pressure waves to the piston, piston rings and other components. Knock must be limited due to the potential for significant engine damage. There is typically an efficiency penalty for operating strategies that mitigate knock, including delayed spark timing and operating the engine fuel-rich.

Manufacturers are building vehicles with smaller turbocharged engines (downsizing) and with powertrain controls aimed at lowering engine speed (downspeeding). Downspeeding and downsizing of SI engines can promote improved efficiency because these engines are typically more efficient at lower speeds and higher loads. However, engines operating at these conditions are more prone to engine knock; mitigating knock through adjustment of spark timing and/or fuel enrichment is done at the expense of efficiency. When an engine at a given speed point is commanded to increase load such that knock will begin, the controller will "retard" the spark timing to later in the cycle than would otherwise be optimum for efficiency and power. This spark timing change prevents end-gas knock and is known as knock limited spark advance (KLSA) and some efficiency is lost to avoid knock. At higher loads, the use of further spark retarding can reach a limit (due to excessively high exhaust temperature, for example) and fuel enrichment is also used to meet the load while avoiding knock and engine damaging exhaust temperatures. Enrichment further decreases efficiency and also increases emissions.

The opportunity for further downsizing and downspeeding of engines to improve fuel economy is limited by the available octane rating of fuels. Note that higher octane fuels will allow higher efficiency designs of naturally aspirated and turbocharged engines dedicated to use the high octane fuel.

KNOCK RESISTANCE OF ETHANOL-GASOLINE BLENDS

The tendency of an SI engine fuel to resist auto-ignition and engine knock is measured as the octane number, a critical performance parameter for SI engines. In the United States, the octane number at the retail pump is given as the anti-knock index (AKI), the average of the RON and the motor octane number (MON), AKI = ½(RON + MON). The differences between the RON and MON test methods are fuel-air charge temperature and engine speed; RON testing uses a comparatively low fuel-air charge temperature and slower engine speed, whereas the MON test is conducted at a significantly higher fuel-air charge temperature and faster engine speed. For modern light-duty SI engines, knock resistance is known to be well correlated with RON.

Given the high RON of ethanol (109), it is commonly blended into a sub-octane blendstock for oxygenate blending (BOB) having a RON of approximately 84 to 88 to produce finished gasoline having adequate knock resistance (in terms of the anti-knock index). Ethanol has a nonlinear effect on the RON of the finished blend, with a diminishing effect as the ethanol content is increased. The increase in RON depends on the starting RON of the BOB, but it increases to around 100 to 105 at E50. With addition of ethanol, the typical 87 AKI E10 can produce a 99-100 RON E25.

Fuel knock resistance for direct injection engines is enhanced by the fact that the fuel-air charge is cooled in the cylinder as the fuel evaporates, reducing the end-gas temperature. This is a major advantage of direct injection over other SI engine fuel system types and is important regardless of the fuel type or the octane number. However, at 25°C, the heat of vaporization of gasoline boiling-range hydrocarbons is 350 to 400 kJ/kg, while that of ethanol is 924 kJ/kg. The heat of vaporization difference is even greater when based on a mass stoichiometric mixture basis, in which the value for hydrocarbon is 22 kJ/kg while that for ethanol is 92 kJ/kg.

An objective in the HOF project was to develop a clear understanding of how to measure heat of vaporization and how to quantify knock resistance for ethanol-gasoline blends. Blends of ethanol at nominal 10, 20, 25, 30, 40, and 50 vol % were prepared with three gasoline blendstocks and a natural gasoline. Natural gasoline, also known as natural gas condensate, is an inexpensive byproduct of natural gas production. Consisting primarily of pentanes, it has low octane number, and is very volatile. Because ethanol is such a potent octane booster, especially with lower octane blendstocks, natural gasoline blends were included in this study.

Heat of vaporization was measured by two methods developed under the project: by differential scanning calorimetry/thermogravimetric analysis and as estimated from detailed hydrocarbon analysis. A striking feature of the results was the insensitivity of the heat of vaporization to hydrocarbon blendstock for temperatures up to 150°C: all four hydrocarbon blendstocks tested had essentially the same heat of vaporization in kJ/kg and the same response to blending with ethanol (Figure 1). These results have been published in a peer-reviewed journal (Chupka, 2015).

The base gasoline and ethanol blends were evaluated in a single-cylinder engine developed from a 2009 model year GM Ecotec 2.0 liter LNF-series engine with a wall-guided direct-injection combustion system. Knock-limited spark advance was measured in spark timing sweep experiments at a nominal load of 925 kPa net mean effective pressure, 1500 rpm, and an intake air temperature of 35°C (measured at the intake port). A relatively low engine speed was used because a longer combustion duration increases exposure of the unburned end-gas to heat and pressure, making the engine more sensitive to autoignition and knock. The load and intake air temperature were selected to ensure the engine could operate on the 88 RON hydrocarbon base gasoline. A plot of KLSA versus RON is shown in Figure 2, which shows that for heats of vaporization ranging from 353 to 527 kJ/kg, RON is an excellent predictor of KLSA under these engine operating conditions.

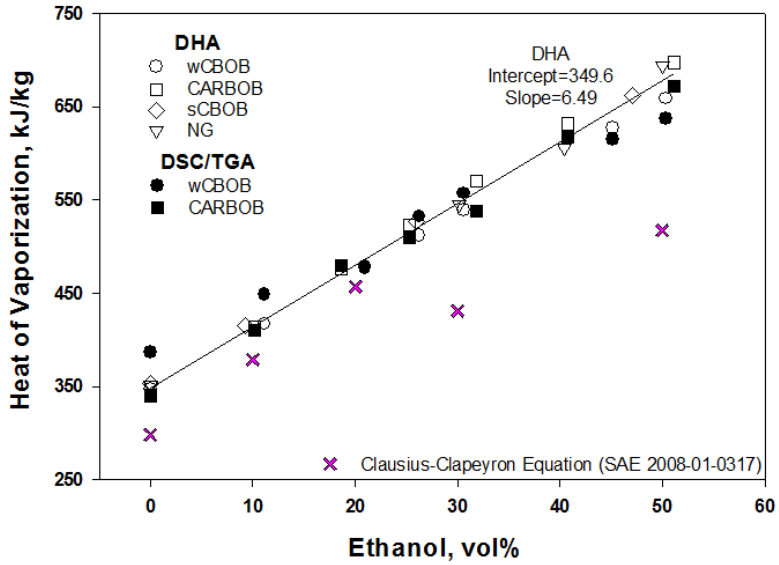


Figure 1. Heat of vaporization as a function of ethanol content measured by differential scanning calorimetry/thermogravimetric analysis (California Reformulated Gasoline Blendstock for Oxygenate Blending blends) at 23°C and by detailed hydrocarbon analysis (all blends) at 25°C.

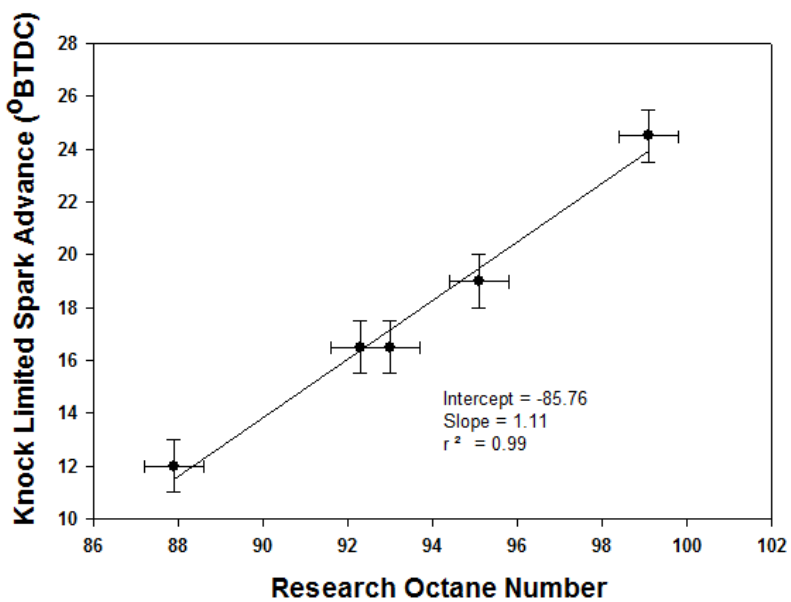


Figure 2. KLSA versus RON. The E50 blend is not included because KLSA could not be reached at the test load.

The results demonstrate that under relatively moderate load conditions in current-technology engines, heat of vaporization is not a factor in engine knock resistance. However, under more extreme conditions enabled by boosted engines using large amounts of spark timing retard to control knock, heat of vaporization may play a role. Additionally, it may be possible to calibrate future high-efficiency engines to take advantage of the heat of vaporization by, for example, injecting a fraction of the fuel after the intake valve closes. These results and associated discussion have been published (Sluder et al, 2016) and the possibilities are being examined under ongoing DOE-sponsored research.

EFFECTS OF HIGH OCTANE FUEL IN A DEDICATED VEHICLE

It is essential to demonstrate the benefits a HOF paired with powertrains optimized for efficiency by taking full advantage of this fuel's properties. To demonstrate the potential efficiency and fuel economy benefits of high-octane mid-level ethanol blends in a dedicated vehicle, a Cadillac ATS equipped with a 2.0 liter turbocharged, direct-injection engine and manual transmission was acquired. A test plan was developed to explore HOF powertrain optimization using this vehicle as a platform; first with the vehicle in unaltered form and then with a series of physical modifications to the engine and vehicle combined with using chassis dynamometer settings to experimentally simulate alternative vehicle configurations.

To downspeed the engine in the ATS vehicle, larger-diameter drive wheels were procured. In addition, with support from General Motors (GM), a custom 2.85:1 differential was acquired to replace the factory 3.27:1 gear set to further downspeed the system. The combination of the larger drive wheels and 2.85 gear set lowered the engine speed by 20%. GM also provided an instrumented cylinder head to permit measurement of cylinder pressure and combustion phasing, and a nondisclosure agreement was executed to permit sharing of a proprietary engine calibration tool.

In the first phase of the research, the factory compression ratio of 9.5:1 was used for baseline experiments with fuels ranging from 87.5 AKI (91 RON) to 101 RON and ethanol levels ranging from 0 to 30%. In the second phase of experiments, the factory compression ratio was retained while downspeeding was implemented with the aforementioned tires and differential. Additionally, downsizing was effectively achieved by evaluating the vehicle at an increased test weight and increased road load forces, simulating installation of the 2.0 liter engine in a mid-size 4,750 pound sport utility vehicle (SUV).

Fuel economy improvements with HOF were demonstrated with the factory pistons along with downspeeding and downsizing, which forces the engine to operate at higher loads. The engine is more knock-prone under these conditions, and increasing the octane level through the addition of ethanol allows more efficient combustion phasing. Figure 3 shows the gasoline equivalent fuel economy for the Cadillac ATS on the high-load US06 cycle for both the stock setup and the downsped condition. The US06 test requires high engine loads and thus causes the engine controller to retard the ignition timing to suppress knock. Therefore, increasing the octane level allows for improved combustion phasing and improved fuel economy, even in the stock condition. Downspeeding the engine requires even higher loads, which would be expected to further exacerbate knock. As shown in Figure 3, the high octane E30 yielded an efficiency improvement of more than 5% over the 88 AKI E10 in the stock setup. Downspeeding improved fuel economy with all fuels relative to the stock condition. Most notable is that a 10% efficiency improvement was demonstrated on this cycle with high-octane E30 in the downsped condition compared with the stock condition with regular E10. Note that in Figures 3, 4 and 5 the fuel economy (E0 MPGeq) represents miles per gallon normalized to the 97 RON E0 (93 AKI) fuel based on lower (volumetric) heating value.

Similar results for the Highway Fuel Economy Test (HFET) are shown in Figure 4. The HFET is a fairly light load test with mild accelerations, an average speed of 48 mph, and a top speed of only 60 mph. For most vehicles, the HFET is not a knock-limited cycle; however, with extreme downspeeding, the ATS is apparently knock-limited with the 88 AKI E10 so that the HOF allows for improved efficiency.

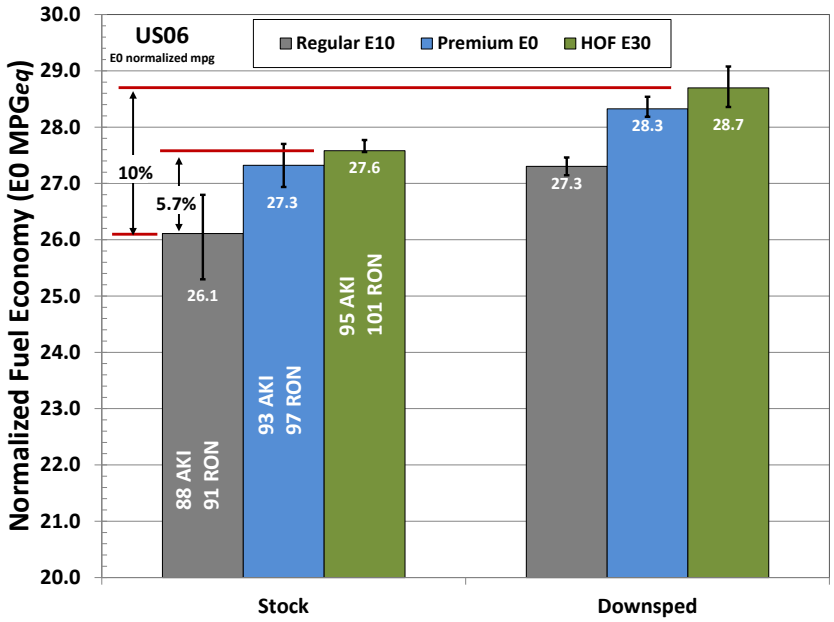


Figure 3. Gasoline equivalent fuel economy for a Cadillac ATS on high-load US06 cycle for stock and downsped conditions with three fuels. Range bars indicate maximum and minimum results for multiple tests.

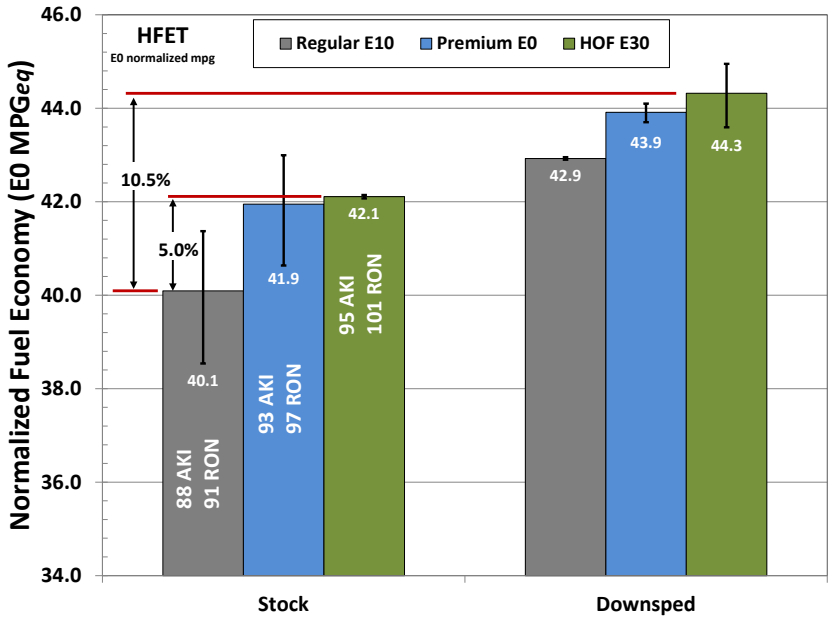


Figure 4. Gasoline equivalent fuel economy for a Cadillac ATS on the Highway Fuel Economy test for stock and downsped conditions with three fuels. Range bars indicate maximum and minimum results for multiple tests.

The Cadillac ATS equivalent test weight (ETW) is 3,750 pounds. Setting the vehicle dynamometer to simulate a Cadillac SRX SUV with a 4,750 ETW and higher road load further loaded the engine, essentially simulating installing the 2.0 liter ATS powertrain in a larger SUV. In these downsped/downsized experiments, the high-octane E30 yielded a 4% efficiency improvement over the regular E10 on the HFET and more than a 10% improvement over the certification database fuel economy for the same vehicle equipped with a naturally-aspirated V6 (Figure 5).

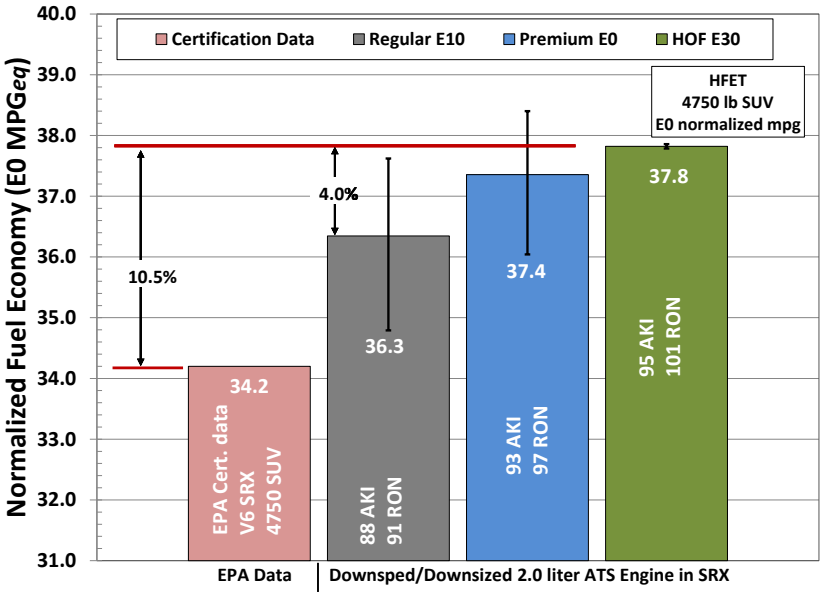


Figure 5. Highway fuel economy test results for downsped/downsized case. EPA certification data for a Cadillac SRX V6 are shown for comparison. Range bars indicate maximum and minimum results for multiple tests.

In phase 3 of the effort, the 10.5:1 compression ratio pistons were installed in the engine. These custom pistons were iteratively designed by KS Kolbenschmidt GMBH, and static and dynamic engine models were exercised by GM to ensure there would be no mechanical interference between the custom pistons and the cylinder head or valves. Following design approval by GM, custom 10.5:1 and 11:1 pistons were fabricated. Upon installation of the 10.5:1 pistons, the engine ran normally for a short time; but engine problems (unrelated to the pistons) precluded completion of the high-compression experiments before publication of this summary report.

EFFECTS OF HIGH OCTANE FUEL ON LEGACY VEHICLES

A small pilot study was conducted to explore the potential performance benefits of high octane ethanol blends in the legacy fleet (Thomas, et al., 2015). There are more than 18 million FFVs currently on the road in the United States, vehicles capable of using any gasoline/ethanol blend from E0 to E85. If currently available FFVs can realize a performance advantage with a high octane ethanol blend such as E25 or E30, then perhaps consumer demand for this fuel can serve as a bridge to future dedicated vehicles. Experiments were performed with four FFVs using a 10% ethanol fuel (E10) with 88 AKI, and a market gasoline blended with ethanol to make a 30% by volume ethanol fuel (E30) with 94 AKI. The RONs were 92.4 for the E10 fuel and 100.7 for the E30. General Motors (GM), Ford and Chrysler have produced the vast majority of FFVs on the road; GM has produced over half of these. Thus two GM vehicles and one each from Ford and Chrysler were recruited for the study, including

- 2014 GMC Sierra pickup truck, 4.3 liter V6 direct-injection engine
- 2014 Chevrolet Impala, 3.6 liter V6 direct-injection engine
- 2013 Ford F150 pickup truck, 5.0 liter V8 port-fuel injected (PFI) engine
- 2013 Dodge minivan, 3.6 liter V6 PFI engine

All four vehicles were naturally-aspirated; the two GM vehicles had gasoline direct-injection engines and the Ford and Dodge vehicles featured port fuel injection. Significant wide-open-throttle performance improvements were measured for three of the four FFVs running the high-octane E30 blend, with one vehicle showing no change. The most significant performance benefit was noted on the GMC Sierra FFV, as shown in Figure 6. This performance gain was noted to be comparable to that for a similar Chevrolet Silverado tested with E85 (*Car and Driver,* 2014). Consistent with expectations, fuel economy measurements over the standard city and highway certification cycles tracked the energy density of the test fuels, indicating insignificant knock-limited operation with the E10 base fuel on these light load cycles.

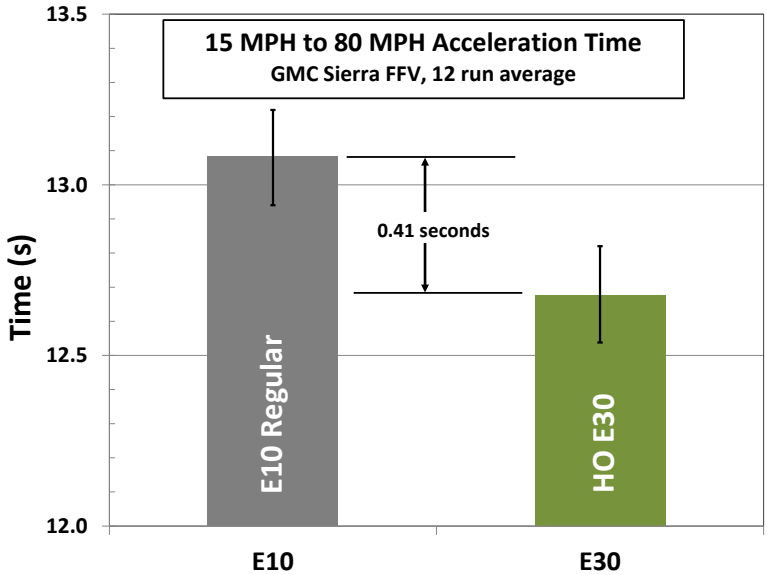


Figure 6. Acceleration time for GMC Sierra FFV using regular E10 and high octane E30 fuel. Range bars show maximum and minimum for 12 tests.

Experiments with a 2014 Ford Fiesta (non-FFV) vehicle with a small turbocharged direct-injection engine were conducted with a regular grade of gasoline without ethanol (E0) and a splash blend of this same fuel with 15% ethanol by volume (E15). The addition of 15% ethanol increased the RON from 90.7 for the E0 to 97.8 for E15. Significant improvements in wide-open-throttle and thermal efficiency performance were measured for this vehicle when fueled with the high-octane E15. It achieved near volumetric fuel economy parity on the aggressive US06 drive cycle, demonstrating the potential for improved fuel economy in forthcoming downsized, downsped engines with HOF.

Figure 7 compares E15 fuel economy on a relative basis with E0 performance in the Ford Fiesta to highlight the improved efficiency for high-octane E15 despite the lower heating value. The expected drop in miles per gallon is 5.6% for E15 versus E0 (based on volumetric energy density ratio), and is denoted by the horizontal red line in the figure. Note that the E15 fuel economy was considerably higher for all tests. For the US06 cycle, volumetric fuel economy parity was almost realized with E15, indicating a 4.6% improvement in thermal efficiency. These results were due to the apparent knock-limited operation on the high-load US06 cycle for this small, turbocharged engine. HOF enables less spark retard and significantly improved efficiency. These results are consistent with those reported by others with turbocharged, direct-injection engines (Jung, 2013; Leone, 2014). Note that the energy density difference between E0 and E15 is very similar to that expected between E10 and E25. Note also that no changes were made to the Fiesta's shift schedule. Hardware and software changes to future vehicles using high-octane mid-level blends would be expected to enable greater efficiency gains from downspeeding. It is

important to note that the results for this EcoBoost Fiesta are not representative of what might be expected from the majority of legacy or current production vehicles.

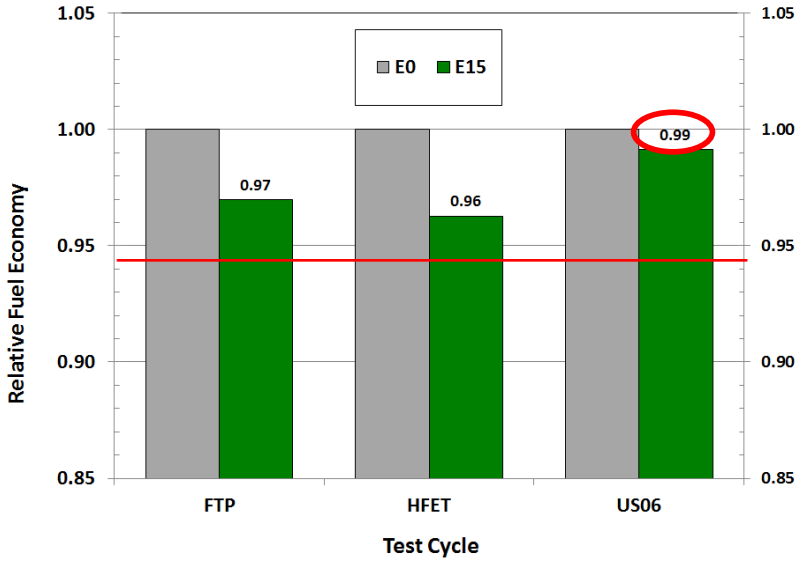


Figure 7. Relative fuel economy for regular E0 and high-octane E15 fuel in a Ford Fiesta. The red line indicates the expected fuel economy with E15 based on the volumetric heating value ratio of the fuel.

Results of vehicle experiments in this program indicate the following:

- High-octane mid-level ethanol blends improved the acceleration performance of legacy FFVs.
- HOF can improve the efficiency of vehicles equipped with turbocharged, direct-injection engines by more than 5%.
  - Efficiency improvements of 5% allow for "volumetric fuel economy parity"; that is, the efficiency gain in future HOF vehicles fueled with E25 would essentially return the same fuel economy as in comparable present-day vehicles fueled with regular E10, despite the lower energy density associated with higher ethanol blending.

WELL-TO-WHEELS GREENHOUSE GAS EMISSIONS ANALYSIS OF HOF

The objective of the well-to-wheels (WTW) analysis is to model petroleum refining to produce RON 100 final gasoline products with a range of ethanol blending levels and gasoline blendstocks . Such blendstocks matched to these different levels of ethanol require different petroleum refining operations during production (Hirshfeld, 2014). Addressing these various blending options is especially important given that US refineries may face the increased use of both heavy crudes, such as oil from the Canadian oil sands, and very light crude shale oil from shale formations such as Bakken and Eagle Ford, and the predicted changeover in product slates such as reduced gasoline production and increased diesel production. The energy and GHG emission intensity differences among these HOF options from petroleum refinery LP modeling, together with upstream production of different crude types and ethanol, are incorporated into the GREET model for WTW simulations of energy and GHG effects.

The WTW GHG emissions impacts of HOF relative to current gasoline requires accounting for vehicle efficiency gains with HOF, refinery operation changes to produce HOF, and the GHG emissions changes from blending corn and cellulosic ethanol into HOF. Detailed refinery LP simulations supplied the WTW analysis with changes in energy intensities and GHG emissions of various gasoline streams for a range of HOF market shares (3 to 71% of the total gasoline market in 2020–2030) and ethanol blending levels (E10, E25, and E40). The WTW analysis was conducted in two phases where two different types of refinery models were used. In the phase 1 analysis, ANL investigated three major refinery configurations (cracking, light coking, and heavy coking) in Petroleum Administration for Defense Districts (PADDs) 2 and 3. In the phase II analysis, ANL employed regionally aggregated refinery models for 6 different regions: PADDs 1, 2, 3 and 4, PADD 5 without California (CA), and CA individually (due to significant differences in CA refineries and regulations compared to others in PADD 5). Moreover, ANL examined several refinery capital expansion options for E10 HOF production cases.

Figure 8 summarizes the GHG reductions of HOF vehicles from miles per gallon of gasoline-equivalent (MPGGE) gains of 5 and 10%, ethanol blending, and changes in refinery operation with HOF production estimated in the phase II analysis. The results show that the impacts of HOF introduction on WTW GHG emissions were dominated by vehicle efficiency gains resulting from the use of HOF and the specific ethanol blending levels. The production efficiencies of gasoline blendstocks for oxygenate blending for various HOF blend levels (E10, E25, and E40) had only a small impact on WTW GHG emissions.

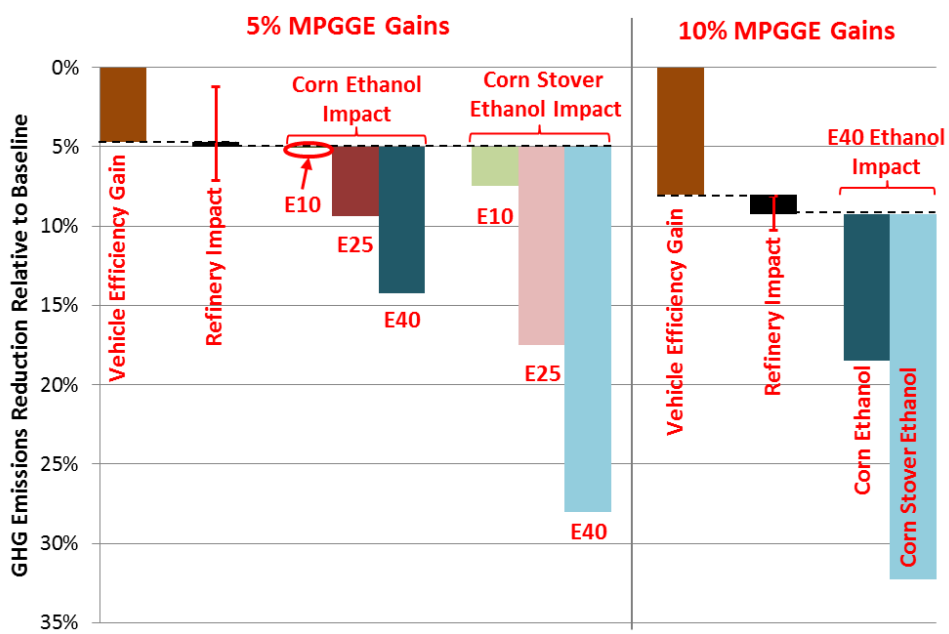


Figure 8. WTW GHG emissions reductions in vehicles fueled by HOFs with different ethanol blending levels relative to regular gasoline (E10) baseline vehicles.

These results from aggregated refinery LP models were generally consistent with those from configuration refinery LP models in the phase I study. The 5 and 10% MPGGE gains by HOF vehicles reduced the WTW GHG emissions by 4 and 8%, respectively, relative to baseline E10 gasoline vehicles. Additional 4 and 9% reductions in WTW GHG emissions can be realized with E25 and E40 blending of corn ethanol, respectively (corn ethanol GHG reductions were simulated with GREET). With corn stover ethanol blending, the additional WTW GHG reductions were 2, 12, and 23% for E10, E25 and E40, respectively. On the other hand, the changes in refinery operations needed to produce HOFs with various

HOF market shares and ethanol blending levels had a much smaller impact on changes in WTW GHG emissions (~1%). The WTW analysis shows that ethanol can be a major enabler in producing HOF and can result in additional reductions in WTW GHG emissions compared with regular E10 gasoline.

Additionally, our regional WTW analysis in Figure 9 showed that the WTW GHG emission reductions by HOF vehicles fueled by E25 HOF relative to E10 baseline vehicles are fairly consistent at 8–9% (or 36–40 g CO_2e/mile driven) throughout all regions when corn ethanol is used for ethanol blendstock. The reduction in the WTW GHG emissions is driven largely by the low GHG emissions associated with ethanol blendstock and the (assumed) 5% vehicle efficiency gain. The key driver for the regional differences in the WTW GHG emissions is the crude quality, in addition to refinery operation. For example, the WTW GHG emissions of PADDs 2 and 4, in which a large amount of Canadian oil sands are consumed, were much greater compared to other regions.

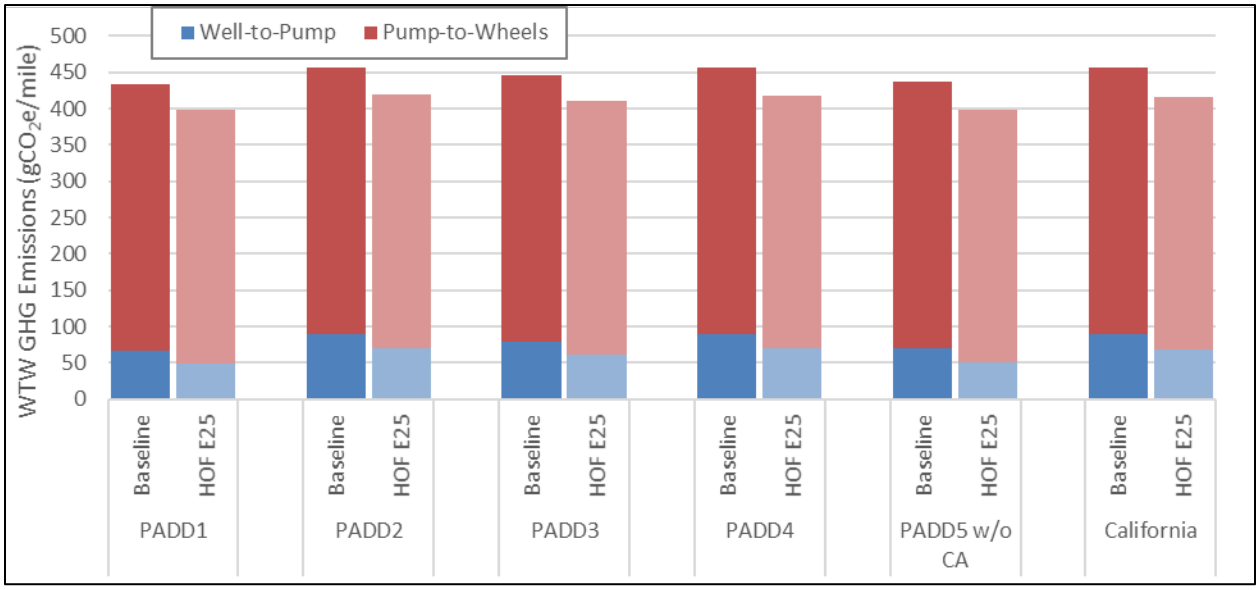


Figure 9. WTW GHG emissions (g CO_2e/mile driven) by HOF vehicles fueled with E25 HOF as compared with regular gasoline vehicles in the non-HOF baseline scenario by region.

As the ethanol blending levels are assumed to increase beyond 25%, more gasoline blendstocks shift from high octane, mid-level ethanol gasoline to gasoline available for export. It is interesting that the efficiency of refining the total gasoline blendstocks (domestic regular and HOF gasoline plus export gasoline) was also unchanged with different ethanol blending levels and market shares. However, many changes in gasoline components (e.g., reformate, alkylate, naphtha) were observed in the domestic gasoline blendstock and export gasoline pools. This is likely a result of simply moving HOF gasoline components displaced by ethanol into the export pool.

MARKET ANALYSIS

Analysis was performed assessing the economic and regulatory barriers to the introduction of a 25% and a 40% ethanol HOF into the market, including options for overcoming these barriers. This included investigation of attractions and deterrents for HOF introduction for key stakeholder (market) groups and assessment of market potential. The four stakeholder groups included fuel producers/ distributors, fuel retailers, vehicle manufacturers, and consumers. Assessments included the market effects and benefits of

HOF with regard to increasing ethanol use; achieving the RFS2 (or variant) in a timely, cost-effective way; reducing fuel costs, and providing consumer and economy-wide benefits. Results included ways of enhancing the HOF business case that circumvent difficulties faced by E85 and E15 (Johnson et al., 2015).

The participation of four main stakeholder groups was predicated upon the benefits of HOF outweighing the costs. Drivers using HOF have the potential to benefit from projected fuel cost savings, reduced price volatility, increased torque in performance applications, and the energy security and environmental attributes. Vehicle manufacturers could benefit from HOF as a means to meet future fuel economy and GHG requirements and as a way to increase torque in performance applications. Fuel retailers could obtain higher per-gallon profit margins from HOF than from gasoline, could see increased visits to their stores as a result of the potentially lower price of HOF versus gasoline, and could use HOF as a means to differentiate their stations from the competition. Fuel producers have the potential to benefit from HOF as a way to comply with RFS2, because the boost in ethanol demand could come at a strategic time for the transition to cellulosic ethanol, and because it could enable the use of less expensive fuel blendstocks.

Despite the potential benefits of HOF, there are also barriers and associated costs that must be resolved before it is adopted at large scale. Thirty of these barriers were identified through interviews with 16 companies and industry associations representing fleet managers, individual drivers, vehicle manufacturers, vehicle dealers, retail fuel stations, ethanol producers (corn and cellulosic), large oil companies, and midstream fuel distributors. This barrier identification was supplemented by information from literature reviews and HOF-related workshops. Ninety-four potential strategies to curtail these barriers were also identified and explored. Complementary subsets of these strategies were grouped into eight deployment scenarios.

The eight deployment scenarios were modeled by the Automotive Deployment Options Projection Tool (ADOPT) to estimate the adoption rate of HOF vehicles. All scenarios showed the potential for HOF vehicles to comprise a substantial percentage (43−79%) of the light-duty vehicle stock by 2035. In general, more HOF vehicles were adopted if HOF was E40, because they offer greater fuel cost savings and offer vehicle manufacturers a greater GHG emissions benefit than if the HOF were E25. The estimated HOF vehicle penetration from ADOPT was then used as an input to analyze potential impacts of HOF on the fuel supply chain. The Biomass Scenario Model (BSM) and the BioTrans model were used for this scenario analysis. The two models are complementary because they focus on different ways that HOF-related investments could be made along the fuel supply chain.

The modeling analyses concur that feedstock availability and cost are not expected to be obstacles to the substantial development of a HOF market, across all of the scenarios considered. In numerous scenarios, HOF costs were sufficiently competitive that a substantial market share was attained—up to 75 billion gallons of E40 or 30 billion gallons of fuel ethanol by 2035. This would meet over 60% of light-duty vehicle fuel demand in that year, according to projections from the ADOPT model. However, all scenarios fell short of 100% of the fuel demand of light-duty vehicles and were therefore limited. The limiting factors affected the eight scenarios in the following pattern:

1. Recognizing that regulations not taking HOF into account would be a limiting factor, most scenarios included the following assumptions:

    a. HOF is registered as a fuel and listed as a certification fuel.

    b. RFS2 is set to increase predictably, so that renewable identification number prices remain within historic levels.

c. Future fuel economy and GHG regulations are set so their accounting systems adequately reward the production of HOF vehicles.

2. Fuel retailers' investment in HOF-compatible equipment was a limiting factor in many scenarios. At varying degrees of market penetration, the economics were marginal for certain retailers to invest. Retailer decisions to invest in HOF equipment were no longer the limiting factor if the following elements were in place:

   a. The retailer is incentivized to invest through a grant, rebate, or tax credit. Scenarios in which incentives covered 40% of investment had greater market penetration, which increased even more when 80% of costs were covered.

   b. Retail equipment cost is reduced by incentivizing equipment manufacturers, by assisting in development of equipment, by subsidizing the equipment, or through economies of scale. These strategies assume a competitive market in which savings to equipment manufacturers result in lower equipment price.

   c. Only HOF-compatible equipment is sold in advance of HOF introduction, which would effectively reduce the up-front cost for retailers that had retired and replaced their equipment after normal useful life.

3. The number of new biorefineries that can be constructed in a year was the limiting factor in scenarios that were not limited by the retail investment barrier, especially in the early years of rapid-growth scenarios. This constraint resulted in a higher ethanol price, which could subsequently deter the use of HOF. This barrier was adequately curtailed in scenarios where:

   a. Enough time passed to allow biorefinery construction to catch up with ethanol demand. This happens around 2025 in applicable cases.

   b. Biorefinery construction was performed at an annual rate greater than previously seen in the United States.

4. HOF vehicle adoption was the limiting factor for the two scenarios in which adequate retailer investment had been made and biorefinery construction had caught up with demand. The specific level of HOF vehicle adoption depended on a number of factors:

   a. More HOF vehicles are adopted if HOF is E40 because it offers greater fuel cost savings to drivers and greater fuel economy/GHG emissions benefits to vehicle manufacturers under future regulations that sufficiently reward the fuel economy benefits associated with HOF.

   b. Proactive vehicle conversion schedules, in which entire model lines are converted to HOF vehicles, result in greater estimated HOF vehicle adoption than conversion schedules that follow market demand.

   c. ADOPT estimated that a $2,500 incentive to the driver would significantly increase HOF vehicle adoption.

The need for feedback loops between the vehicle model and the fuel models was identified during this analysis. Such feedback loops were established between the ADOPT and BSM models, a baseline scenario was run, and sensitivity analyses were performed on variables deemed influential. These runs provided new insight into the interrelationships between the vehicle and fuel supply industries under

various deployment, incentive, and external conditions. These insights were reported in Newes et al. 2015. The combined vehicle and fuel supply model is also available to use in future market analyses.

HIGH OCTANE FUEL INFRASTRUCTURE

RETAIL STATIONS

A major objective was to identify the issues associated with storing and dispensing a new fuel in the existing infrastructure, considering both the aboveground and the underground equipment. A service station consists of many interconnected pieces of refueling equipment necessary to deliver fuel to vehicles. There are approximately 60 pieces of equipment at a station designed to handle fuel and vapor and regulations require nearly all of this equipment to be compatible with the fuel stored. Two questions considered in introducing a new fuel to existing infrastructure are:

- Is the infrastructure compatible?
- Is the equipment listed by a third party or approved by the manufacturer for use with a specific fuel?

A significant amount of research and regulatory action has addressed these concerns with positive progress toward enabling the use of ethanol blends higher than E10 in existing and upgraded equipment. The issues for deploying equipment handling higher ethanol blends center on cost considerations and station knowledge of fueling equipment - rather than technical issues. A potential barrier is that stations are not required to keep records of equipment if they are selling E10 or lower ethanol gasoline. This makes it difficult to determine if existing equipment is compatible with various ethanol blends. For aboveground equipment, UL-listed E25 and E85 equipment (which satisfies federal and local regulations) is available. The price premium for E25 equipment is minimal compared to conventional E10 equipment, whereas the price premium is significant for E85 due to the use of specialized metals (Johnson et al., 2015; Moriarty, Kass and Theiss, 2014). Interested parties have suggested testing E25 equipment to see if it can be recertified by UL for E30 or E40. Credit card companies are switching to chip and pin cards, which will result in many dispensers being upgraded or replaced to accommodate the new cards by October 2017. This is a large, near-term opportunity to upgrade dispensers to accommodate higher-level ethanol blends.

EPA's Office of Underground Storage Tanks regulates underground storage tanks (USTs) per Code of Federal Regulation (CFR) Title 40 Subtitle 1 Subchapter 1 Parts 280-282. The federal UST regulation was updated in October 2015 with section CFR 280.32 in the 2015 UST regulation providing clarity to the 1988 compatibility requirement by specifying additional compatibility requirements for owners and operators wishing to store certain regulated substances, including fuels containing more than 20 percent biodiesel (and 10 percent ethanol). All portions of an UST system must be compatible with the fuel stored. Demonstrations of compatibility must be provided for the: tank, piping, containment sumps, pumping equipment, release detection equipment, spill equipment, and overfill equipment. The requirements are:

1. Owners of USTs switching to store blends containing greater than 20% biodiesel or 10% ethanol must notify their implementing agency (usually a state office) 30 days prior to switching fuels to store an E10+ (or B20+) blend.

2. Owners of USTs storing greater than E10 must demonstrate compatibility through either:

    a. Certification/listing of equipment for use with the fuel stored by a nationally recognized, independent testing laboratory or

b. Equipment or component manufacturer approval for use with the fuel stored. This written statement must affirm compatibility and list the specific ranges of biofuel blend the equipment or component is compatible with or
c. Use of another option determined by the implementing agency to be no less protective of human health and the environment.

3. Owners of USTs storing fuels containing greater than 10% ethanol must maintain records demonstrating compatibility as long as the fuel is stored.

TERMINALS

Terminals are an important part of the transportation fuel supply chain moving products to end-user markets. Their primary function is to store and distribute fuels. The Oil Price Information Service reports that there are 1,296 terminals storing transportation fuel nationwide, and nearly all either store ethanol or are capable of storing it (OPIS, 2015). Terminals store all fuel components separately (i.e., gasoline blendstock, ethanol, additives), and they are blended in-line as they are delivered to transport trucks. Many companies with terminals are also obligated parties under RFS2, and they may see a benefit in deploying more ethanol capacity to meet their volume requirements and see it as a potential revenue stream through renewable identification number markets.

While there are no technical barriers to storing more ethanol, there are several non-technical factors that could limit increased deployment of ethanol at terminals, including: terminal companies report that nearly all tanks are in-use, and there is a lengthy permit process to build a new tank if needed; land to add new tanks and off-loading facilities may not be available; increased truck traffic to deliver ethanol could be problematic for some terminals; pipeline companies own many terminals and lease tanks to customers under long-term contracts for storage of specific fuels, thus there would have to be a strong business case to motivate terminals to add off-loading, and loading bay equipment and additional tanks if no existing ones are available. Many terminals receive ethanol from rail trans-modal facilities and further study is required to determine the ability of trans-modal facilities to handle more ethanol.

LOW-COST POTENTIAL HOF BLENDSTOCKS

The important objective of quantifying the potential of low cost HOF formulated with natural gasoline was addressed by the following activities:

- Examine the ranges of composition and properties for natural gasoline sold in the US market.
- Determine the properties of blends of various natural gasolines and ethanol at different blend levels.
- Develop a model to predict natural gasoline–ethanol blend vapor pressure for Flex Fuel (ASTM D5798 compliant fuel).

Samples of natural gasoline were obtained from eight sources covering the range available in the market. These were assessed for chemical composition using detailed hydrocarbon analysis (ASTM D6730: high-resolution gas chromatography to identify individual components of gasoline) and by benzene analysis (ASTM D3606). Sulfur, Reid vapor pressure (RVP), and RON were determined by appropriate ASTM methods.

A subset of samples meeting the current benzene limit and the proposed Tier 3 sulfur limit, and covering the range of composition and properties, were blended to produce E30 (HOF) and Flex Fuel (E51, E70,

and E83). The vapor pressure, RON, and MON were measured. For the E30 blends, NREL also measured the distillation curve (ASTM D86) and vapor lock protection class (Alleman, 2015).

NREL has used a modeling approach based on the Wilson equation and on considering the gasoline as a pseudo-component to successfully predict the vapor pressure of gasoline–alcohol blends to within 0.7 kPa (Christensen, 2011), which is more precise than the repeatability of the vapor pressure measurement method (2 kPa for ASTM D5191). This modified Wilson method was applied to the blends to determine its suitability for predicting RVP to eliminate the need for RVP testing of the final blend, thus eliminating the need for additional testing at the terminal. The modeling approach showed that the RVP for the finished fuel could successfully be estimated from the RVP of the blend components for this work. These results have been published in a peer-reviewed journal (Alleman, 2015).

Key outcomes from this research (Alleman, 2015) include:

- Natural gasoline samples in this project consisted of 80–95% paraffinics, 5–15% naphthenics, 3% or less aromatics, and the balance olefins. Paraffins were typically n-pentane and iso-pentanes.

- Benzene content ranged from approximately 0.1 to 1.2 wt %, so blends of E30 and E40 would meet EPA limits for benzene content in gasoline.

- Sulfur content ranged between 4 and 145 ppm. Assuming an ethanol content of 51 vol % (Flex Fuel minimum ethanol content), a natural gasoline blendstock would be required to have 20 ppm sulfur or less for the finished fuel to meet the EPA Tier 3 gasoline sulfur limit.

- Vapor pressure (ASTM D5191-13) ranged from 12.9 to 14.6 psi. Because of the high vapor pressure, over 70 vol % ethanol could be blended into Flex Fuel while still meeting the class 4 (wintertime) minimum vapor pressure requirement of 9.5 psi. For blending of class 1 (summertime) Flex Fuel, a minimum of 74 vol % ethanol was required to stay below the 9 psi upper limit on vapor pressure.

- Modeling of vapor pressure using universal quasichemical functional-group activity coefficients (UNIFAC) and Wilson equation-based approaches provided good agreement with experimental data for most samples.

- The RON for the natural gasoline ranged from 67 to 72. When it is blended with ethanol, the 91 RON level typical of finished regular gasoline would be met with approximately 30 vol % ethanol. Natural gasoline is a volatile, low-cost blendstock for Flex Fuel. For a high-octane mid-level blend, natural gasoline could only be used as a blending component.

CONCLUSIONS

The experimental and analytical results of this study considered together show that HOF, specifically mid-level ethanol blends (E25-E40), could offer significant benefits for the United States. These benefits include an improvement in vehicle fuel efficiency in vehicles designed and dedicated to use the increased octane. The improved efficiency of 5-10% could offset the lower energy density of the increased ethanol content, resulting in volumetric fuel economy parity of E25-E40 blends with E10. Most of the flex-fuel vehicles on the road today would be expected to have faster acceleration using HOF, which offers a marketing opportunity in the near term. Furthermore, dedicated HOF vehicles would provide lower well-to-wheel GHG emissions from a combination of improved vehicle efficiency and increased use of ethanol. If ethanol were produced using cellulosic sources, GHG emissions would be expected to be up

to 30% lower than those from E10 using conventional ethanol and gasoline. Refinery modeling suggests that refiners could use higher levels of ethanol to meet potentially high market shares of HOF.

Analysis of the HOF market and the primary stakeholders reveals that the automotive OEMs, consumers, fuel retailers, and ethanol producers all stand to benefit to varying degrees as HOF increases its market share. The results depend on the underlying assumptions; but HOF offers an opportunity for improved fuel economy, and these dedicated vehicles are likely to be appealing to consumers. The possible limiting constraints to significant HOF market penetration were identified. Regulatory uncertainty and insufficient retailing investment were considered the most likely constraints to limit the introduction of HOF. HOF could be limited by the rate of construction of additional integrated biorefinery capacity, and poor dedicated HOF vehicle penetration would also limit the overall HOF market. Feedstock availability was not found to limit the growth of HOF.

It would be a significant benefit if a new fuel utilized the existing infrastructure. Our findings were that neither technical nor materials obstacles are likely to prohibit HOF, but new aboveground equipment compatible with HOF will need to be installed. Sufficient capacity was found to allow the introduction of HOF at the nation's terminals.

Overall blendstock costs are not a significant barrier to HOF introduction and the low cost of natural gasoline makes it attractive to consider for a blending component. The properties of HOF, when using natural gasoline as the sole blendstock, can be predicted with sufficient accuracy using industry-accepted models for RVP. The use of these models to predict final RVP of the finished blend eliminates the need for additional test capability at terminals and reduces a barrier to introduction of this type of HOF blend.

REFERENCES

Alleman, T. L., R. L. McCormick, and J. Yanowitz, "Properties of Ethanol Fuel Blends Made with Natural Gasoline," *Energy Fuels* **29** 5095-5102 (2015).

Anderson, J. E., et al., "High Octane Number Ethanol-Gasoline Blends: Quantifying the Potential Benefits in the United States," *Fuel* **97**, 585–594 (2012).

Car and Driver, "Drivelines: Chevrolet Silverado V6," *Car and Driver* **59**(9), March 2014, pp. 102–13 Available at http://www.caranddriver.com/reviews/2014-chevrolet-silverado-v-6-instrumented-test-review. Accessed July 2016.

Christensen, E., et al., "Renewable Oxygenate Blending Effects on Gasoline Properties," *Energy Fuels* **25**(10) 4723–4733 (2011).

Chupka, G.M., et al., "Heat of Vaporization Measurements for Ethanol Blends Up To 50 Volume Percent in Several Hydrocarbon Blendstocks and Implications for Knock in SI Engines" *SAE Int. J. Fuels Lubr.* 2015, doi:10.4271/2015-01-0763.

Hirshfeld, D. S., et al., "Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content," *Environ. Sci. Technol.* **48**, 11064–11071 (2014). doi:10.1021/es5021668

Johnson, C., Newes, E., Brooker, A., McCormick, R., Peterson, S., Leiby, P., Martinez, R.U., Oladosu, G. and Brown, M.L. (2015). High-Octane Mid-Level Ethanol Blend Market Assessment. NREL/TP-5400-63698.

Jung, H., et al., "Fuel Economy and CO_2 Emissions of Ethanol-Gasoline Blends in a Turbocharged DI Engine," *SAE Int. J. Engines* **6**(1) (2013). doi:10.4271/2013-01-1321

Leone, T., et al., "Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO_2 for a Turbocharged DI Engine," *SAE Int. J. Fuels Lubr*. **7**(1), 9–28 (2014). doi:10.4271/2014-01-1228.

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

Newes, E., Johnson, C., Brooker, A., Peterson, S. (2015). Draft Integrated Market Analysis of High-Octane Mid-Level Ethanol Blends.

Oil Price Information Service (OPIS). 2015. Petroleum Terminal Encyclopedia. Available for purchase at: http://www.opisnet.com/products/liquid-terminals-directory.aspx

Sluder, C., Szybist, J., McCormick, R., Ratcliff, M. et al., "Exploring the Relationship Between Octane Sensitivity and Heat-of-Vaporization," *SAE Int. J. Fuels Lubr.* 9(1):80-90, 2016, doi:10.4271/2016-01-0836.

Splitter, D. A., and J. P. Szybist, "Experimental Investigation of Spark-Ignited Combustion with High-Octane Biofuels and EGR. 2. Fuel and EGR Effects on Knock-Limited Load and Speed," *Energy & Fuels* **28**(2), 1432–1445 (2014). doi:10.1021/ef401575e

Splitter, D. and J. Szybist, "Intermediate Alcohol-Gasoline Blends, Fuels for Enabling Increased Engine Efficiency and Powertrain Possibilities," *SAE Int. J. Fuels Lubr.* **7**(1) (2014). doi:10.4271/2014-01-1231

Szybist, J., et al., "Investigation of Knock Limited Compression Ratio of Ethanol Gasoline Blends," SAE Technical Paper 2010-01-0619, 2010, doi:10.4271/2010-01-0619.

Szybist, J. and B. West, "The Impact of Low Octane Hydrocarbon Blending Streams on the Knock Limit of "E85," *SAE Int. J. Fuels Lubr.* **6**(1),44–54 (2013). doi:10.4271/2013-01-0888

Thomas, J. F., B. H. West, and S. P. Huff, *Effects of High-Octane Ethanol Blends on Four Legacy Flex-Fuel Vehicles, and a Turbocharged GDI Vehicle*, ORNL/TM-2015/116, March 2015. Available at http://info.ornl.gov/sites/publications/files/Pub54888.pdf

Evaluation of Costs of EPA's 2022-2025 GHG Standards
With High Octane Fuels and Optimized High Efficiency Engines
AIR, Inc.[1]
September 16, 2016

1.0 Introduction

In August of 2012, EPA released a final rule setting greenhouse gas (GHG) standards for cars, light trucks, and SUVs for model years 2017-2025. [2] The final standards for model year 2025 were projected to result in a fleetwide CO_2 tailpipe emissions of 163 g/mi, if achieved exclusively through fuel economy improvements. The final standards were based on vehicle footprints, so that all vehicles would achieve GHG emission reductions, regardless of size. EPA expected that improvements would come from advances in engines and transmissions, weight reduction, improved aerodynamics, advances in internal combustion engines, along with increases in hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs). New 2025 model year vehicles (cars and trucks combined) were estimated to cost $1,800 more than 2016 model year vehicles.

Since the standards were finalized with a long lead-time before they took effect, EPA committed to releasing a Technical Assessment Report (TAR), in 2016 to reassess the feasibility of the 2022-2025 model year standards. This report was released in July of 2016. The report generally reaffirmed the feasibility of the original GHG standards.

One key, inexpensive technology that could improve vehicle fuel economy, which was not evaluated by the either the Final Rule or TAR, is an increase in engine compression ratio (CR) that is enabled by a high-octane fuel. Current production engine compression ratios are limited by the octane of gasoline in the U.S. If octane is increased, engine compression ratios can increase, increasing engine efficiency and reducing GHG emissions. So called premium fuel with higher octane content does enable higher compression ratios, but the price difference between premium and regular fuel, along with the concern that vehicles designed for premium would most often be operated on regular because of the price difference in the fuels, effectively limits the amount that automakers can increase compression ratios in the U.S. A high-octane mid-level ethanol blend, however, is likely to be very price-competitive with current regular fuel. If such a fuel were widely available at a competitive cost to regular, auto manufacturers would be likely to employ increased compression ratios to reduce GHG emissions. There is much research going on in this area related to how much engine compression ratios could be increased with mid-level ethanol blends, such as E25 or E30. EPA has also indicated that high-octane fuels could be examined to improve GHG emissions post-2025.[3]

---

[1] This study was made possible through a research grant from the Minnesota Corn Research and Promotion Council.
[2] EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017-2025 Cars and Light Trucks, Regulatory Announcement, USEPA, OTAQ, EPA-420-F-12-051, August 2012.
[3] Technical Assessment Report, pg. 5-42, "this program [Co-Optima] has the potential to provide meaningful data and ideas for GHG and fuel consumption reductions in the light-duty vehicle fleet for 2026 and beyond".

The attractiveness of a high-octane mid-level ethanol blend goes beyond just meeting the GHG standards. The Renewable Fuel Standard (RFS) reduces up-stream GHG emissions reductions from future fuels by requiring increasing amounts of low-GHG fuels. The increase in these required low GHG fuels, however, has declined from the levels originally intended because development of cellulosic biofuel is taking somewhat longer than originally anticipated, and because gasoline marketers have not developed refueling infrastructure for E85 due to slow sales of E85. The slow sales of E85, however, are a function of how E85 has been priced relative to its energy content. The availability of a high octane mid level blend for vehicles purposely designed for this fuel, would spur additional advances in cellulosic biofuel, thereby increasing the benefits of the RFS.

To attempt to fill the gap in the Final Rule and TAR analysis on high-octane fuels, this study evaluates the possible implementation of higher compression ratio (HCR) engines using high-octane low carbon (HOLCF) fuel in the 2022-2025 model years, and the impacts on the costs of EPA's GHG standards. In this study, we assume the same tailpipe GHG standards as EPA's final rule, so the environmental benefits of this HCR/HOLCF strategy *exceed* the benefits of the current TAR, because under HCR/HOLCF, the tailpipe benefits are the same as the TAR, while the upstream benefits of the RFS are greater than currently estimated by EPA.

In this study, we evaluate the impacts of the widespread availability of a 98-RON E25 fuel.[4] We mainly focus on the impacts on the TAR-estimated costs, and for simplicity ignore the potential increases in RFS benefits, which are significant. There are three general parts to the analysis. In the first part, we estimate how much of an increase in CR is possible with 98-RON E25 based on existing research, and the effects on tailpipe GHG emissions. In the second part, we estimate the costs of compression ratio increases, and also 98-RON E25 fuel costs, relative to regular E10. In the third part, we implement high compression ratio engines and the total engine plus fuel costs into EPA's modeling system, and compare program costs and technology penetrations before and after this implementation.

We do not evaluate the impacts of a premium fuel on compression ratios and overall program costs. The main reason for this is cost – the current price differential of premium over regular in the US is about $0.26/gallon. Using EPA's mileage accumulation rates for passenger cars, an assumed fuel economy of 45 mpg, and a 7% discount rate, the net present value of the fuel costs is $860, close to the average new vehicle cost in the TAR. While the use of premium fuel to improve compression ratio would reduce technology costs to meet the GHG standards, with the historical and expected price differential between regular and premium, it is unlikely that premium would be used extensively by vehicle owners, unless regular fuel were eliminated at service stations.

The study is organized into the following sections:

[4] The selection of this level of ethanol is for the purposes of this study. If automakers chose to certify on a different level of ethanol, the benefits of E25 in this study could be scaled.

2.0 Effect of Increased Compression Ratio on GHG Emissions

There have been a number of studies over the past several years examining the effect of ethanol on increasing octane, and the effect of octane on increasing compression ratios and engine efficiency. This section reviews several recent studies, and develops an estimate of the reduction in tailpipe GHG emissions that are possible with a high-octane ethanol fuel like 98-RON E25.

2.1 SAE 2013-01-1321

In a 2013 study by Ford Motor Company, a 2013 production 3.5L direct injection turbocharged V6 engine was engine dynamometer tested comparing the standard 10.0:1 compression ratio with 87 AKI E10 commercial fuel with 11.9:1 compression ratio with 96 RON E20 and 101 RON E30.[5] The E20 and E30 fuels were prepared by splash blending denatured ethanol into the E10 base fuel (fuel properties are shown in Table 1). The engine dynamometer testing simulated a light duty pickup truck operating on the EPA city and highway and US06 driving schedules. No engine calibration or hardware changes were made in addition to piston changes to vary compression ratio.

Compared to the E10 standard configuration tests, the E20 fuel with high compression ratio demonstrated 5% reduction in CO_2 emissions on all driving schedules with similar volumetric fuel economy (mpg) results. E30 fuel and high compression ratio showed 5% reduction in CO_2 on the city and highway schedules and 7.5% reduction on the high speed and load US06 schedule, while fuel economy was 3% lower on the city and highway schedules and about equal on US06.

Table 1. Test Fuel Properties – SAE 2013-01-1321

Fuel	E10	E20	E30
Ethanol (%v)	10.2	20.4	31.5
NHV (MJ/kg)	41.5	39.7	37.7
HoV (MJ/kg)	0.41	0.48	0.55
Specific Gravity	0.743	0.749	0.755
RON	90.8	96.2	100.7
MON	84.1	86.1	87.9
AKI	87.4	91.1	94.3

Based on brake mean effective pressure (BMEP) data, the 96-RON E20 enabled a 1.9 increase in compression ratio and increased thermal efficiency without reaching the engine knock limit due to higher RON and the increased charge cooling and increased sensitivity of the higher ethanol content. The data indicated that a higher compression ratio could have been tolerated with E30, perhaps demonstrating additional improvements in efficiency, CO_2 and fuel economy, but that condition was not tested.

[5] Leone, T., Anderson, J. et al., Fuel Economy and CO2 Emissions of Ethanol-Gasoline Blends in a Turbocharged DI Engine, SAE 2013-01-1321, April 8, 2013.

Although little data existed in the literature, an approximately 4% to 5% increase in engine efficiency was measured as a result of increasing the compression ratio by 1.9 at part load conditions most important for typical drive cycles. Notably, this study demonstrates that the loss in energy content of E20 compared to E10 was more than offset by the increase in compression ratio, such that the volumetric fuel economy (MPG) and driving range were similar to the baseline condition.

2.2 SAE 2013-01-1634

In another 2013 study by Ford and AVL Powertrain Engineering, a 5.0L direct injection turbocharged V8 engine was tested on an engine dynamometer at part load conditions on E0 gasoline and 100% ethanol (as a substitute for E85) to compare and understand ethanol related engine efficiency improvements reported in previous studies.[6] Properties of the E0 and E100 test fuels are shown in Table 2 below, with E85 also shown for comparison. Single cylinder engine modeling was also used. An approximately 4% improvement in Brake Thermal Efficiency was measured. Major contributors were cooler exhaust gas due to charge cooling related to the higher heat of vaporization of ethanol and lower adiabatic flame temperature. An approximately 7% lower CO_2 emissions were measured, with 4% of the reduction due to improved thermal efficiency and 3% due to the higher hydrogen to carbon ratio (lower carbon content) of ethanol. For other ethanol-gasoline blends, the study indicated that the fundamental thermal efficiency and CO_2 emissions benefits would scale approximately linearly with the molar fraction of ethanol in the blend. These benefits are in addition to opportunities for improved efficiency, which are available due to the greatly improved knock resistance of ethanol-gasoline blends. The study helped to explain the fuel economy and CO_2 implications of increased ethanol content in ethanol-gasoline blend fuels, and its conclusions are expected to be generally applicable to automotive engines with minor variations due engine and fuel system design.

Table 2. Test Fuel Properties – SAE 2013-01-1634

Fuel	Gasoline	E85	E100
Ethanol (%v)	0	82.7	100
RON	90.7	109	109
MON	83.4	90	90
H/C (mole)	1.83	2.72	3.0
NHV (MJ/kg fuel)	43.4	29.2	26.9
HoV (kJ/kg fuel)	350	850	920
Density (kg/L)	0.748	0.785	0.796

[6] Jung, H., Shelby, M., Stein, R. et al., Effect of Ethanol on Part Load Thermal Efficiency and CO2 Emissions of SI Engines, SAE 2013-01-1634, April 8, 2013.

2.3 SAE 2014-01-1228

A more recent Ford and AVL Powertrain engine dynamometer study tested a 3.5L direct injected turbocharged V6 engine[7] with similar fuels and engine compression ratios to the 2013 study referenced above. Compared to the 2013 study, a 13.0:1 compression ratio (CR) was added to the 10.0:1 standard and 11.9:1 ratios. As in the previous study, the engine dynamometer testing simulated a light duty pickup truck. Also, several octane "matched blend" fuels were added to the E10 91 RON base fuel, E20 96 RON and E30 101 RON splash blended fuels from the previous study. For the matched blend fuels, hydrocarbon properties were adjusted in the E20 and E30 fuels to maintain constant 91 RON and MON. Two additional fuels were tested, an E85 108 RON and E10 98 RON (also called E10 premium). As predicted in the previous study, the 101 RON E30 fuel enabled the 13:1 CR with better knock performance than the E10 91 RON base fuel and standard 10:1 CR. No knock benefit was exhibited in the 91 RON E20 and E30 matched blend fuels compared to E10 91 RON.

Table 3. Properties of Splash Blended Test Fuels in SAE 2014-01-1228

	Splash Blends			Match Blends				
Fuel	E10-91RON	E20-96RON	E30-101RON	E10-91RON	E20-91RON	E30-91RON	E10-98RON	E85-108RON
Ethanol (%v)	10	20.4	31.5	10	20.5	29.5	9.8	84.3
RON	90.8	96.2	100.7	91.8	90.6	90.7	99.0	~108
MON	84.1	86.1	87.9	84.1	83.2	82.7	91.4	~90
H/C (mole)	2.00	2.08	2.18	2.11	2.11	2.20	2.18	2.89
NHV (MJ/kg)	41.5	39.7	37.7	42.0	40.1	38.6	42.5	29.0
HoV (MJ/kg)	0.41	0.48	0.55	0.41	0.48	0.54	0.41	0.86
Specific Gravity	0.743	0.749	0.755	0.735	0.749	0.760	0.725	0.777

Compared to the E20 96 RON fuel, the E10 98 RON (or E10 premium) fuel enabled the 11.9 CR with similar knock behavior. Both fuels would be expected to have similar tank-to-wheels CO_2 emission while the E20 96 RON would be expected to have an advantage in well-to-tank and overall lifecycle CO_2. The E10 premium fuel would have about 3.6% better volumetric fuel economy due to higher energy content and a slightly higher knock limit near MBT due to higher RON, while the E20 96 RON showed an advantage in knock behavior at full load BMEP.

CO_2 emissions were substantially reduced with the E20 96 RON and E30 101 RON fuels compared to the E10 91 RON base fuel.

[7] Leone, T., Anderson, J., Stein R. et al., Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO_2 for a Turbocharged DI Engine, SAE 2014-01-1228, April 1, 2014.

Table 4. Reduction in CO_2 Emissions		
Cycle	96-RON E20 with 11.9 CR	98-RON E30 with 13.0 CR
EPA City/Highway	4.8-5.1%	6.0%
US06	4.9-5.7%	9.1%

The matched blend fuels showed only modest (less than 1%) CO2 reductions similar to a Flexible Fuel Vehicle that is optimized for 91 RON fuel. While the E20 96 RON fuel had about 4% less energy content than the E10 91 RON base fuel, the efficiency benefit at 11.9 CR more than offset the lower energy content such that volumetric fuel economy in MPG and driving range were essentially equivalent. For the E30 101 RON fuel and 13.0 CR, the efficiency benefit mostly offset the lower energy content such that MPG was reduced about 2% for the EPA city/highway schedules and improved by 1% for the US06 test.

2.4 2015 National Academy of Sciences (NAS) Study[8]

The NAS study, released in 2015, reviewed the technologies that would be used to meet EPA and NHTSA's 2017-2025 model year standards, and the agencies' modeling efforts. The report made a number of recommendations to the agencies to consider for the mid-term TAR.

The NAS report did review several fuel consumption reduction technologies that were not considered in the final 2017-2025 rule. One of the technologies evaluated was a "high compression ratio with high octane gasoline".

The NAS concluded that:

> At part load, up to 3 percent reduction in fuel consumption for naturally aspirated engines might be realized if compression ratio is increased from today's typical level of 10:1 to approximately 12:1, which is approximately a 1.5 percent reduction in fuel consumption per 1.0 compression ratio increase.

The NAS further estimated an incremental direct manufacturing cost for strengthened pistons and reduced engine tolerances of $50-$100 for a compression ratio increase on regular fuel (no octane increase), and $75-$150 to implement increased compression ratios on high octane regular fuel. The variation in cost is based on engine/car size. NAS did not estimate the cost to increase compression ratio on a high-octane mid-level ethanol blend. Our discussions with auto manufacturers have indicated they think there is very little, and perhaps no cost to increase compression ratio for a mid-level ethanol blend, and that this is a very attractive option to reduce GHG emissions.

[8] "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles", National Academy of Sciences, Table S.2, ISBN 978-0-309-37388-3, 2015.

2.5 2015 E, S&T Study by Leone, Anderson, Davis, Iqbal, Reese, Shelby, and Studzinski[9]

This 2015 literature review covered a number of very relevant topics related to the driving forces for evaluating engine, vehicle, and fuel changes. In particular, the paper points out that increased fuel economy requirements are leading to engine design changes such as increased turbocharging, cylinder deactivation, downsizing and down-speeding, and all of these changes are leading to increased engine operation at higher loads, where engines are knock-limited (in other words, further trends in these directions cannot continue unless the knock-limited region is reduced). The paper further evaluates recent developments in measuring and characterizing octane measurements and their effect on engine knock resistance.

An empirical expression was developed that allows the estimation of expected vehicle efficiency, volumetric fuel economy, and CO2 emission benefits for future vehicles through higher compression ratios for different assumptions on fuel properties and engine types. The method utilized data from a 3.5 L GTDI engine tested with CRs of 10:1, 11.9:1, and 13:1 run on an engine dynamometer. The method describes 3 types of efficiency gains from higher octane ethanol fuels – an efficiency improvement due to the use of higher compression ratios, an efficiency gain due to engine downsizing, and an efficiency gain from ethanol itself, which is related to the chemical properties of ethanol, including its higher heat of vaporization.

Table 5 shows these estimated efficiency gains, tailpipe CO2 reductions, and fuel economy changes for a 96-RON E20 and a 101-RON E30, relative to a 91-RON E10. For the 96-RON E20 fuel, the efficiency gain from compression ratio is 3.48%, with 0.5% from higher ethanol content and 0.35% from downsizing. These values are higher for a 101-RON E30 fuel. The estimated CO2 reduction for the E20 fuel is -4.5% and for E30 is 7%. There is little change in volumetric fuel economy for either fuel, as the efficiency gain basically counteracts the reduction in ethanol energy content.

Table 5. Estimated Benefits of Higher Octane Ethanol Fuels Estimated in Paper (Relative to 91-RON E10)

Parameter	96-RON E20	101-RON E30
Efficiency gain from higher compression ratio	3.48%	5.35%
Efficiency gain from higher ethanol content	0.51%	1.07%
Efficiency gain from downsizing	0.35%	0.54%
Total efficiency gain	4.4%	7.0%
Tailpipe CO2 change	-4.5%	-7.0%
Fuel economy change	0.6%	-1.2%

[9] "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency, Leone, Anderson, Davis, Iqbal, Reese, Shelby, Studzinski, Environmental Science and Technology, 2015, 49, 10778-10789.

2.6 July 2016 Study by Oak Ridge National Laboratory (ORNL)

Considerable engine and vehicle based research has been performed in the past several years at the US Department of Energy Oak Ridge National Laboratory (ORNL) to determine the potential efficiency and performance benefits of high octane mid-level ethanol fuel blends. A recent report documented the results of a dedicated vehicle test program using a current production 2.0L direct injection turbocharged Cadillac ATS, with driveline modifications to "downspeed" the engine by about 20% as one of many strategies to meet new fuel economy and greenhouse gas emission requirements. [10]

Engine "downsizing" was also simulated by testing the vehicle at 4,750 pound test weight common to a mid-size sport utility vehicle Test fuels ranged from 87 AKI base fuel to 101 RON, and E0 to E30. The production 9.5:1 CR was used for this phase of the ORNL testing. Engine efficiency as measured by gasoline equivalent miles per gallon[11] was improved by about 10% with the E30 101 RON fuel compared to the baseline vehicle condition and E10 87 AKI (91 RON) fuel on the US06 and the EPA highway fuel economy schedules.

As a continuation of the ORNL high octane mid-level ethanol blend research, a vehicle based chassis dynamometer study is currently underway at ORNL sponsored by the National Corn Growers Association (NCGA) to evaluate CO2 emissions performance of a modified 2.0L direction injection turbocharged Cadillac ATS with E10 87 AKI regular grade gasoline and splash blended E25 98 RON fuel. Vehicle modifications include replacement pistons to increase CR from production 9.5:1 to 10.5:1 and driveline modifications to "downspeed" the engine by about 20%. Test conditions will include 4,750- pound test weight to simulate a "downsized" engine installation in a light duty mid-sized utility vehicle. Based on several previously referenced research studies and numerous other studies in the public literature comparing current production engines and vehicles to increased CR with high-octane mid-level ethanol blend fuels, a demonstration of substantial CO_2 emission benefits is expected. Test results from the study are expected near the end of the 2016 calendar year.

2.7 GHG Emission Reduction Used for High Compression in This Study

Most of the previous studies indicated a GHG emissions reduction in 4-8% range for E20-E30 fuels with RONs of 96-101. In this study, we will base our estimate of the GHG emissions reduction on the 2015 E, S&T paper, which developed comprehensive impacts for a 96-RON E20 and a 101-RON E30. The tailpipe GHG emissions change for a 98-RON E25 would be one-half of the reductions of these two fuels, or 5.75%. We will round this to 6%. In addition to 6%, we will estimate the impacts of reductions of 4% and 8%.

---

[10] West B. ORNL, McCormick, R. NREL, Wang M. ANL et al., Summary of High-Octane, Mid-Level Ethanol Blends Study, ORNL/TM-2016/42, July 2016.

[11] Fuel economy in MPG normalized to 97 RON E0 (93 AKI) fuel based on lower (volumetric) heating value.

3.0 Compression Ratio Costs and Fuel Costs

3.1 Compression Ratio Costs

The NAS study covered in the previous section estimated a $75-$150 cost for increased compression ratios for engines using higher- octane regular fuel (without ethanol). This is for improved pistons and rings and reduced tolerances. We also contacted automakers, and their impression was that costs of increased compression ratio would be near zero, especially if it were accomplished during normal engine re-design cycles. [12]

Table 6 shows costs estimated by EPA for various technologies for conventional vehicles. The last row shows the estimated effectiveness and cost of increased compression ratios. Increasing compression ratios on conventional engines appears to be one of the most effective, and least costly, alternatives to increasing engine efficiency.

Table 6. Comparison of Increased CR with Other Technologies

Technology	Effectiveness (%) – EPA	Total Cost ($) – EPA
Improved Lubricants	0.5-0.8	3
Engine Friction Reduction 1	2.0-2.7	46-123
Engine Friction Reduction 2	3.4-4.8	101-254
Cylinder Deactivation	3.9-5.3	130-230
Intake Cam Phasing	2.1-2.7	49-97
Dual Cam Phasing	4.1-5.5	100-214
Discrete Variable Valve Lift	4.1-5.6	171-353
Continuous Variable Valve Lift	5.1-7.0	256-512
Increased Compression Ratio	6-7	75-150 (NAS)

For the purposes of this analysis, we will assume a $100 total cost for increasing compression ratios for engines for a 98 RON E25 fuel.

3.2 Fuel Costs - Forecasting Fuel Prices Through 2040

The current version of EPA's OMEGA model uses the Energy Information Administration (EIA) 2015 Annual Energy Outlook (AEO 2015) future forecast of retail gasoline to estimate the fuel savings (in 2013 dollars) that consumers realize as a result of more stringent fuel economy standards. In order to add a new technology of high compression spark ignition engines and high-octane fuels to the OMEGA model, it is necessary to use the information in AEO 2015[13] to establish forecasts out to 2040 for

[12] During a Co-OPTIMA Stakeholder "Listening Day" held June 16-17, 2015, several auto makers indicated that "if 100 RON was available today, manufacture of compatible engines would be a given." "Co-Optima Stakeholder Listening Day Summary Report", US Department of Energy, National Renewable Energy Laboratory, June 2015.

[13] The prices for retail gasoline and wholesale ethanol are shown in AEO 2015 for select years only. The year-by-year values were provided by EIA directly. The assumptions used in generating these numbers were found in the document "Assumptions to the Annual Energy Outlook", EIA, September, 2015.

high-octane regular gasoline with its octane boosted to premium gasoline levels using additional ethanol.

3.2.1 Methodology

The two relevant values forecast in AEO 2015 are the retail price of gasoline, and the wholesale price of ethanol. For the retail price of gasoline, this is the forecast average price for all blends of gasoline (except E85) and includes all local, state and federal taxes ($0.44 a gallon) and product markups ($0.15). The wholesale price of fuel ethanol is forecast out to 2040 assuming that the volumes of the RFS are met with the following exception:

> The RFS is included in AEO2014, however it is assumed that the schedule for cellulosic biofuel is adjusted downward consistent with waiver provisions contained in the law.

In order to forecast the future costs of mid-level blend fuel, the following steps need to occur. The first is that the wholesale price of regular grade (87 AKI octane) gasoline needs to be determined based upon AEO prices of "Retail Gasoline." This involves unbundling two effects: the removal of taxes and markups from the retail price, and the price impact of premium grade fuel and other ethanol blends on the retail price. Ultimately, it was concluded that these factors could not be unbundled using data from EIA alone, so the average of the weekly price differential between regular and premium blendstock from May 5, 2014 to August 22, 2016 published by Oil Price Information Service was used. This constant ($0.26 a gallon) is used to both convert the AEO 2015 price for all grades of retail gasoline (primarily regular grade and plus premium grade E10) into regular grade E10. The retail price for gasoline shown in AEO 2015 marks up the wholesale price for federal, state and local taxes and retail mark-up. These total $0.59 a gallon.[14]

The second step is that the price of E10 84 AKI gasoline blendstock needs to be determined. With the wholesale price of both E10 (10% ethanol and 90% gasoline blendstock) and ethanol known, it is a simple calculation to determine the implied price of the blendstock. The formula is $P_B = (P_{E10} - 0.1 \text{ X } P_E) / 0.9$ where P_B is the price per gallon of the blendstock, P_{E10} is the price per gallon of E10 and P_E is the price per gallon of ethanol.

Once the price of the 84 AKI gasoline blendstock is known, the wholesale cost of a 25% ethanol 75% gasoline blend can be determined using the formula $P_{E25} = (0.25 \text{ X } P_E) + (0.75 \text{ X } P_B)$ where P_{E25} is the wholesale price per gallon of E25. Adding back in the $0.59 per gallon wholesale to retail constant provides the retail price for E25.

Results of this analysis are shown in Table 7.

[14] "Assumptions to the Annual Energy Outlook," Energy Information Administration, September, 2015.

Table 7. EIA Price Analysis if E25 versus E10

Year	Retail Gasoline	Wholesale to Retail Markup	All grades E10 Wholesale Gasoline	E10 Regular Wholesale Gasoline	Wholesale Ethanol	Price Of Blendstock	Wholesale E25	Retail E25	Cost Difference, E10-E25
2012	$3.72	$0.60	$3.13	$3.10	$2.58	$3.16	$3.01	$3.61	0.11
2013	$3.55	$0.60	$2.95	$2.93	$2.37	$2.99	$2.84	$3.43	0.12
2014	$3.35	$0.60	$2.75	$2.73	$2.19	$2.79	$2.64	$3.24	0.12
2015	$2.31	$0.60	$1.71	$1.69	$2.16	$1.63	$1.76	$2.36	-0.05
2016	$2.63	$0.60	$2.03	$2.01	$2.12	$1.99	$2.03	$2.62	0.01
2017	$2.70	$0.60	$2.10	$2.07	$2.68	$2.00	$2.17	$2.77	-0.08
2018	$2.70	$0.60	$2.10	$2.07	$2.63	$2.01	$2.17	$2.76	-0.07
2019	$2.70	$0.60	$2.11	$2.08	$2.59	$2.02	$2.16	$2.76	-0.06
2020	$2.74	$0.60	$2.14	$2.11	$2.49	$2.07	$2.18	$2.77	-0.04
2021	$2.78	$0.60	$2.18	$2.16	$2.53	$2.11	$2.22	$2.82	-0.04
2022	$2.82	$0.60	$2.22	$2.19	$2.51	$2.16	$2.24	$2.84	-0.03
2023	$2.86	$0.60	$2.26	$2.23	$2.51	$2.20	$2.28	$2.88	-0.02
2024	$2.90	$0.60	$2.30	$2.28	$2.49	$2.26	$2.31	$2.91	-0.01
2025	$2.95	$0.60	$2.35	$2.32	$2.47	$2.31	$2.35	$2.95	0.00
2026	$3.00	$0.60	$2.40	$2.37	$2.45	$2.36	$2.39	$2.98	0.01
2027	$3.04	$0.60	$2.44	$2.42	$2.42	$2.42	$2.42	$3.02	0.03
2028	$3.09	$0.60	$2.49	$2.47	$2.41	$2.48	$2.46	$3.06	0.04
2029	$3.15	$0.60	$2.55	$2.52	$2.39	$2.54	$2.50	$3.10	0.05
2030	$3.20	$0.60	$2.60	$2.57	$2.35	$2.60	$2.54	$3.14	0.06
2031	$3.26	$0.60	$2.66	$2.63	$2.37	$2.66	$2.59	$3.19	0.07
2032	$3.33	$0.60	$2.73	$2.70	$2.41	$2.73	$2.65	$3.25	0.07
2033	$3.40	$0.60	$2.80	$2.77	$2.43	$2.81	$2.71	$3.31	0.08
2034	$3.46	$0.60	$2.86	$2.83	$2.46	$2.88	$2.77	$3.37	0.09
2035	$3.53	$0.60	$2.93	$2.90	$2.49	$2.95	$2.83	$3.43	0.09
2036	$3.60	$0.60	$3.00	$2.97	$2.50	$3.02	$2.89	$3.49	0.10
2037	$3.66	$0.60	$3.07	$3.04	$2.53	$3.10	$2.95	$3.55	0.11
2038	$3.74	$0.60	$3.14	$3.12	$2.57	$3.18	$3.03	$3.62	0.12
2039	$3.83	$0.60	$3.23	$3.20	$2.61	$3.27	$3.10	$3.70	0.13
2040	$3.90	$0.60	$3.30	$3.27	$2.64	$3.35	$3.17	$3.77	0.13
								Average, 2012-2040	0.04

Table 6 shows that, generally, over the projection until 2040, E25 is about 4 cents per gallon lower than E10. In the time period of 2012-2016 using historical data, E25 would be 6 cents per gallon lower than E10. If E25 is 4 cents lower than E10 over the lifetime of a 2025 vehicle, assuming a 45 mpg fuel economy, a 7% discount rate, and the OMEGA mileage accumulation rates for a passenger car, the NPV of this credit for E25 is $132.23. At 6 cents per gallon lower, the credit for E25 is worth $198.35.

3.2.2 Factors That Could Impact These Forecasts

These price forecasts were developed to enable the modeling of a scenario in which a minimum octane standard would be established that would enable automakers to increase the compression ratio of spark ignition engines at the least possible cost. Automakers have shown that a mid-level gasoline-ethanol blend with a Research Octane Number (RON) of at least 98 has nearly optimal CO_2 reduction and cost per mile[15] which is comparable to today's premium grade E10 gasoline. A 98 RON fuel can be produced using today's regular grade gasoline blendstock by increasing the 10% ethanol to 25%, or

[15] USCAR data shown in the presentation "The Increasing Importance of Fuel Octane," Tom Leone, Ford Motor Company at the Society of Automotive Engineers Industry/Government Meeting, January 2016.

E25. While blends between E20 to E40 have been evaluated, this analysis focuses on E25 as typical of a high-octane low carbon fuel formulation.

In order for automakers to be comfortable in significantly increasing the compression ratio of their engines, however, they would need to be assured that there was no danger of that engine inadvertently operating on lower octane fuel. This would require either foolproof misfueling prevention devices or an end to the sale of low octane fuel. For purposes of this analysis, it is assumed that, like the sale of leaded gasoline in the 1970's, EPA would establish a minimum octane rating of 98 RON and set a date after which low octane fuel could no longer be marketed. Or, smart cars and smart fuel pumps would communicate in such as way that cars requiring E25 would not use anything but E25. In any event, this analysis evaluates a long-term steady state situation where fleet turnover to E25 vehicles is nearly complete.

In this analysis, the AEO 2015 prices were used to create these scenarios. Factors that could impact the values calculated for this study include:

- Changes in fuel volume that could increase or decrease the forecast fuel price. For the scenario where regular low octane E10 is replaced with a high octane regular grade E25, the volume changes involved would be an increase in the demand for ethanol and a decrease in the demand for regular grade gasoline blendstock. In this scenario, the amount of the shift in volumes is relatively minor (15% of regular gasoline blendstock would be replaced with ethanol after the minimum octane standard became mandatory). There is a 15% increase in ethanol volumes from 2012 to 2040 already built into the AEO 2015 numbers and hence these price forecasts. Also, the historical record shows that, between 2007 and 2015, ethanol production increased by 127% while the price of ethanol decreased by 37%. There are a number of reasons to believe this relative price insensitivity would apply to the additional volume of ethanol required to change E10 into E25, including:

    - Research underway at the federal level to develop technologies that would reduce the cost of converting cellulosic feedstock to $3 a gallon gasoline equivalent.
    - The recent Billion Ton report indicating that there are significant volumes of harvestable biomass.
    - Idle former sugar cane farms in the Western Hemisphere that could easily be brought back into production.

  Consequently, this analysis uses the AEO 2015 price forecasts for ethanol to hold true under either scenario.

- Changes to infrastructure necessary to enable the scenarios. The infrastructure changes to replace E10 regular with high octane E25 regular, however, are not too complex. A 2012 study by Stillwater Associates to evaluate the distribution costs of

E30 by calendar year 2017 found that distribution costs would range between 0.2 cents and 0.5 cents per gallon, depending on the method used. [16]

Overall, the forecasted prices for E25 in this study are likely not to be significantly affected by consideration of volume and infrastructure costs.

3.3 Total Costs of Increased Compression Ratio and Lifetime Fuel Credit

As indicated in section 3.1, we are assuming a $100 cost for increasing compression ratio of vehicles. However, the lifetime NPV fuel credit (using 7% discount rate) in section 3.2.1 is $132.23. For fuel distribution cost, assuming a 0.4 cent per gallon cost, the lifetime NPV cost (assuming 7% discount) is $13.22. The costs and credits approximately balance each other, therefore for the remainder of this analysis we are estimating zero net cost to the consumer.

[16] The Cost of Introducing an Intermediate Blend Ethanol Fuel for 2017- and- Later Vehicles, study for Air Improvement Resource, Inc, Stillwater Associates, October 17, 2012.

4.0 Incorporating HCR with HOLC fuel into EPA's OMEGA Model

This section explains how we incorporate HCR/HOLC into EPA's OMEGA model, and how the results compare with EPA's default results. We start by examining EPA's results, then we explain the method used, and finally we show the results of HCR/HOLC versus the EPA defaults.

4.1 EPA's Results

Table 8 shows the draft TAR per vehicle costs to meet the 2025 standards, relative to the 2021 model year standards. For GHGs in model year 2025, the costs range between $894 (ICM case) and $1,017 (RPE). These values are directly from Table ES-2 of the TAR. The values reported for the Primary Case reflect the use of Indirect Cost Multipliers (ICM). The sensitivity case utilizes Retail Price Equivalents (RPE). The CAFÉ values reflect RPE values and include civil penalties estimated to be incurred by some models. For the GHG analysis, average costs range between $894 and $1,017.

Table 8. Per Vehicle Average Costs to Meet Model Year 2025 Standards; Draft TAR Analysis Costs are Shown Incremental to the Costs to Meet the Model Year 2021 Standards

	GHG in Model Year 2025		CAFÉ in Model Year 2028	
	Primary Case	RPE Analysis	Primary Case	ICM Analysis
Car	$707	$789	$1,207	$1,156
Truck	$1,099	$1,267	$1,289	$1,096
Combined	**$894**	**$1,017**	$1,245	$1,128

In the first step of incorporating HCR with HOLC fuel into OMEGA, AIR first replicated EPA's analysis. With some effort and EPA's assistance, AIR was able to replicate EPA's result for the GHG Primary Case in 2025 exactly. Some of the key outputs of this analysis are shown in Table 9.

Table 9. Key Outputs of the 2025 Primary GHG Case (Uses ICMs)

Item	Value
Vehicle sales	16,419,435
Total cost ($)	$23.4 billion
Average Cost (relative to 2014 model year)	$1,425
Average cost (relative to continuation of 2021 model year standards)	$894
CO_2 Target (g/mi)	198.83
Final CO_2 (g/mi)	197.79

The total cost of the 2025 model year emission standards is 23.4 billion dollars, and the average cost relative to the 2014 model is $1,425. This is higher than the $894 in the Table 8, because Table 8's costs are relative to the continuation of 2021 standards, where Table 9 costs are relative to the reference vehicle, a 2014 model year vehicle. The 2021

average vehicle cost increment we estimated is $531.01, so $1,425-$531.01 = $893.33. Thus, we have been able to replicate EPA's analysis. A number of cases were run where we replicated the EPA results exactly.

The aggregated results above are estimated from the OMEGA model, which predicts technologies that will be on all cars and light duty trucks to meet the required tailpipe GHG emission standards. There are 2,819 separate vehicle models for all manufacturers in the OMEGA model. Every vehicle model is associated with a vehicle type, of which there are 19 separate types. OMEGA creates up to 50 likely technology packages, which consist of groups of technologies, for every vehicle type. These 50 groups are actually developed by a separate part of the model called the Lumped Parameter Model (LPM). The OMEGA model basically computes the least cost solution to meeting GHG standards for each manufacturer, utilizing all of its models. There can also be more than one technology in the final solution for each vehicle model. The model applies the most cost-effective technologies first, and then continues to apply technologies across different models until the manufacturer meets its emission standard.

Table 10 shows the technologies that are predicted by the OMEGA model to be present on a 2025 Buick Enclave. OMEGA predicts that several technology packages will be present on 2025 Buick Enclaves, however, in reality this may not be realistic (the detailed technologies present on these Technology packages are shown in Attachment 1). Nonetheless, this is what OMEGA predicts.

Table 10. Technologies on a 2025 Buick Enclave Predicted by OMEGA (Central Case using ICMs)

Tech Pkg	Powertrain Type	Sales fraction	Weighted average cost
9	MHEV-48V	25%	$2,146
10	MHEV-48V	55%	
11	ATK	20%	

MHEV = mild hybrid electric vehicle
ATK = Atkinson cycle engine

4.2 Implementation of HCR/HOLCF

The next step was to incorporate HCR/HOLCF. In the previous section (Section 3), we estimated a primary case GHG benefit for HCR/HOF of 6%. In this analysis, we will estimate the impacts of a 4%, 6%, and 8% benefit. Also in the previous section, we evaluated costs of the high compression ratio technology, the HOLCF fuel, and fuel distribution costs, and concluded that the net costs of these 3 items are zero. So, we are estimating the impacts of 3 benefit cases – 4%, 6%, and 8%.

Our first thought was to introduce HCR in the OMEGA model as a new, single technology. However, this technology would not have been recognized by the model and integrated into the existing technology packages without extensive work, so we had to develop an alternative solution.

Our approach was to (1) classify each technology as a conventional vehicle (CV), hybrid electric vehicle (HEV), Atkinson cycle engine, or battery electric vehicle (BEV), and (2) apply the HCR benefit and costs only to conventional vehicles and Atkinson cycle engines not associated with an HEV, and (3) re-run OMEGA to determine the cost differences. We explain this process using the example of Buick Enclave below, assuming a 6% reduction in emissions for a HCR engine, with zero net cost.

The first eleven technology packages for Vehicle Class 8 (midsize MPV V6) are shown in Table 11. Technology Package 0 is the starting point for every vehicle class. The actual technologies for the first 11 Enclave technology packages are shown in Attachment 1 (there are many more technology packages for Enclave, but we only show the first 11). There is no change in the CO_2 emissions or cost for Technology 0 (the starting point). For Tech Package 1, the original CO2 is 327.3 g/mi. Our assumption is that because of its low cost and attractive effectiveness, high compression ratio would be included on all conventional technology packages from Tech Package 1 and higher. The CO_2 emissions of Tech Package 1 are estimated by multiplying the CO_2 emissions of Tech Package 0 by 6% (21.49 g/mi), and subtracting that value from the original Tech Package 1 value (327.3-21.49 = 305.81). This process is carried on for all conventional vehicles, because our assumption is that all conventional vehicles would be equipped with high compression ratio engines.

Table 11. Buick Enclave Technology Packages

Tech #	Type	Original (EPA)		6%, $0	
		CO_2	Cost	CO_2	Cost
0	Conv	358.1	$0	358.1	$0
1	Conv	327.3	$333	305.8	$333
2	Conv	306.3	$485	284.8	$485
3	Conv	272.2	$505	250.7	$505
4	Conv	260.7	$700	239.3	$700
5	Conv	241.9	$1,275	220.4	$1,275
6	Conv	252.7	$947	231.2	$947
7	Conv	247.8	$1,269	226.3	$1,269
8	ATK	231.9	$1,770	218.0	$1,770
9	MHEV-48V	229.7	$1,882	229.7	$1,882
10	MHEV-48V	216.7	$2,314	216.7	$2,314
11	ATK	225.0	$2,017	211.5	$2,017

Tech packages 9 and 10 for the Enclave are 48-volt mild hybrids. To be conservative in our analysis, we have applied no compression ratio reduction in emissions for these vehicles, even though they have an internal combustion engine that would probably benefit from a higher compression ratio engine. Tech package 11 includes an Atkinson cycle engine. Atkinson cycle engines in this context are assumed to have higher compression ratios due to intake and exhaust timing changes. Atkinson cycle engines already have higher compression ratios, however, with a higher-octane fuel, there is the

possibility that the compression ratio could probably be increased from the compression ratio they would be designed for with 87-octane fuel. Thus, there would probably be an efficiency gain to higher compression ratios for Atkinson engines. Thus, we have modeled Atkinson engines by subtracting the 6% reduction in GHG emissions from the EPA CO_2 emissions for that technology package. [17] Six percent of 225 is 13.5 g/mi, so the CO_2 of Atkinson Enclave with increased compression ratio due to high octane fuel would be 211.5 g/mi.

Note that applying the benefit of HCR in this manner is not diminishing the benefits of the other technology packages. For example, the difference in emissions between Tech Package 1 and Tech Package 2 is 21 g/mi CO_2 in both cases. Also, in automatically applying HCR to all conventional technology packages, we are in a sense "forcing" the model to use HCR for all conventional engines. However, with zero or near zero cost and a 6% benefit, the model would have chosen to do that anyway, even if it had been coded as a separate technology. Finally, EPA utilizes a combination of the Lumped Parameter Model and the Alpha model to ensure that it is properly accounting for various synergies between different technologies; i.e., that one cannot just add percent benefits for a selection of different technologies to determine an overall Technology Package percent reduction. We have not put HCR through this fairly rigorous treatment. We have assumed that all of the non-HCR packages have gone through that process, and when we add HCR in, that the benefit is undiminished at 6%. We have also run sensitivity cases at 4% and 8% for the reader to evaluate. While the overall method we have used to model HCR may not be exactly what EPA would do in this circumstance because it does not utilize ALPHA modeling, physical simulations, and the Lumped Parameter Model, we believe the method represents a reasonable first approximation of the effects of higher compression ratios on OMEGA results.

The results of this analysis are shown in Table 12. With higher compression ratio engines included, total costs of the 2025 model year standards are reduced from $23.4 billion to $16.8 billion. Sales[18], CO_2 targets and final CO_2 levels are essentially identical.[19]

---

[17] Some HEVs utilize Atkinson cycle engines. We have assumed no HCR credit for these engines used in HEVs, only ATK engines used without HEV technology.

[18] Reducing the cost of new 2025 vehicles by utilizing lower cost technology should result in some sales increase. For purposes of this analysis, however, it is not necessary to model these increases, so each scenario is modeled on the same sales basis.

[19] While final CO2 levels are the same with higher compression ratio engines, the GHG benefits of EPA's GHG standards utilizing high compression ratio engines enabled by high octane low carbon fuel would be greater than EPA's benefits, because of upstream GHG benefits from the low carbon fuel. We have not quantified these upstream benefits in this analysis.

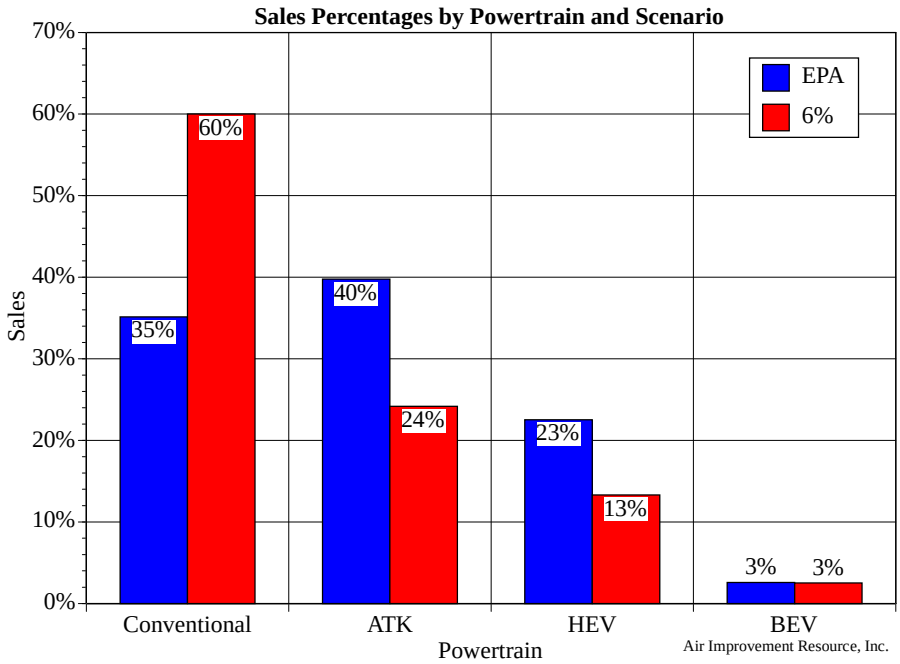
Table 12. Impact of HCR on Model Year 2025 Vehicle Costs		
Item	Without Higher Compression Ratio	With Higher Compression Ratio
Sales	16,419,435	16,419,435
Total Cost Billion ($)	23.4	16.8
Average per vehicle cost $/vehicle	$1,425	$1,021
CO_2 Target (g/mi)	198.83	198.83
Final CO_2 (g/mi)	197.79	197.75

The results for the Enclave are shown in Table 13. The EPA default shows that 80% of Enclave sales in 2025 would be 48V mild hybrids and 20% would be Atkinson cycle engines, while the case with increased compression ratio shows that 100% of vehicles would be conventional (split 75% in Tech package 5 and 25% in Tech package 7).

Table 13. Impact of HCR on Buick Enclave Model Year 2025 Technologies				
Run	Tech Pckg	Powertrain Type	Sales	Weighted Average Cost
EPA Default (without higher compression ratio)	9	MHEV-48V	25.00%	$2,146
	10	MHEV-48V	55.00%	
	11	ATK	20.00%	
6%_$0	5	Conv	75.00%	$1,273
	7	Conv	25.00%	

Figure 1 shows the impact of HCR on 2025 model year sales percentages by powertrain. HCR reduces the conversions to Atkinson cycle and HEVs, but appears to have no effect on the percent of battery electric vehicles.

Figure 1



Figures 2-5 further show the impacts of high compression ratio on 2025 model year fleet technology costs, average vehicle technology costs, average vehicle costs by powertrain type, and sales percentages by powertrain type.

While it was necessary to make some simplifying assumptions to utilize the OMEGA model to obtain these results, we are confident that, if EPA had included this technology package in their OMEGA modeling for the mid-term review, they would have observed similar cost savings for the 2025 model year. The 2025 model year is significant for several reasons:

- It is the last model year considered in the TAR.
- It will be the baseline year for future greenhouse gas emission and fuel economy standards.
- It is the first year that the Co-Optima program indicates a new high-octane fuel could reach the market.[20]

It should also be noted that this analysis was performed to predict what EPA would estimate the potential cost-savings of this new technology would be in 2025. Therefore, we have retained the same assumptions regarding costs as EPA has used. Others, however, calculate costs differently. NHTSA, for example, estimates costs using the

[20] From the TAR discussion of the Co-Optima program, page 5-42 "Two parallel research tracks focus on: 1) improving near-term efficiency of spark-ignition (SI) engines through the identification of fuel properties and design parameters of existing base engines that maximize performance. The efficiency target represents a 15% fuel economy improvement over state-of-the-art, future light-duty SI engines with a market introduction target of 2025."

Retail Price Equivalent Method of mark-up while EPA retains the use of the Indirect Cost Multiplier method. The NHTSA methods result in higher compliance costs than EPA. Therefore, it is quite possible that the actual cost savings will be much greater than the numbers predicted in this study.

Figure 2

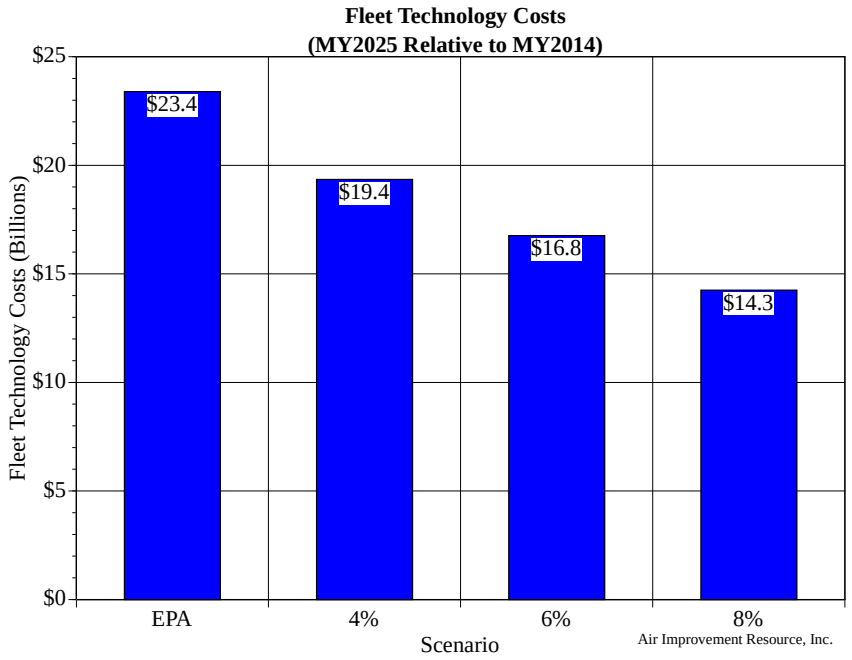


Figure 3

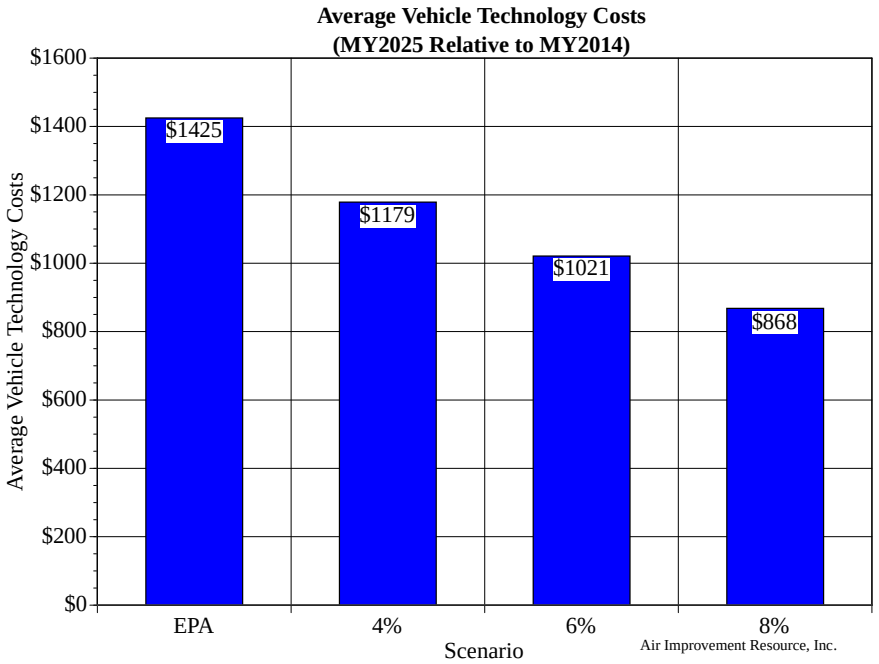


Figure 4

Average Vehicle Technology Costs by Powertrain and Scenario (MY2025 Relative to MY2014)

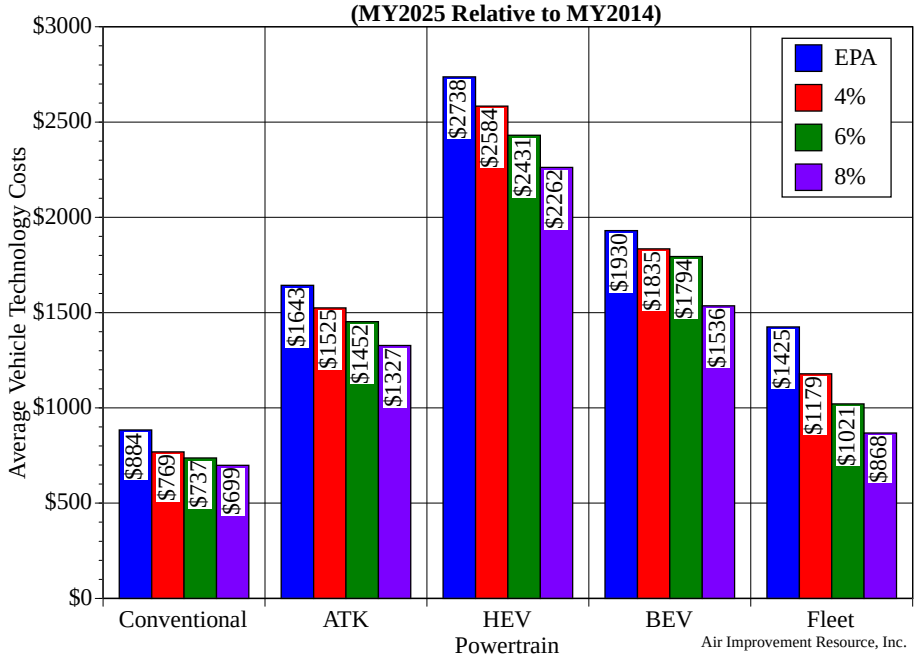
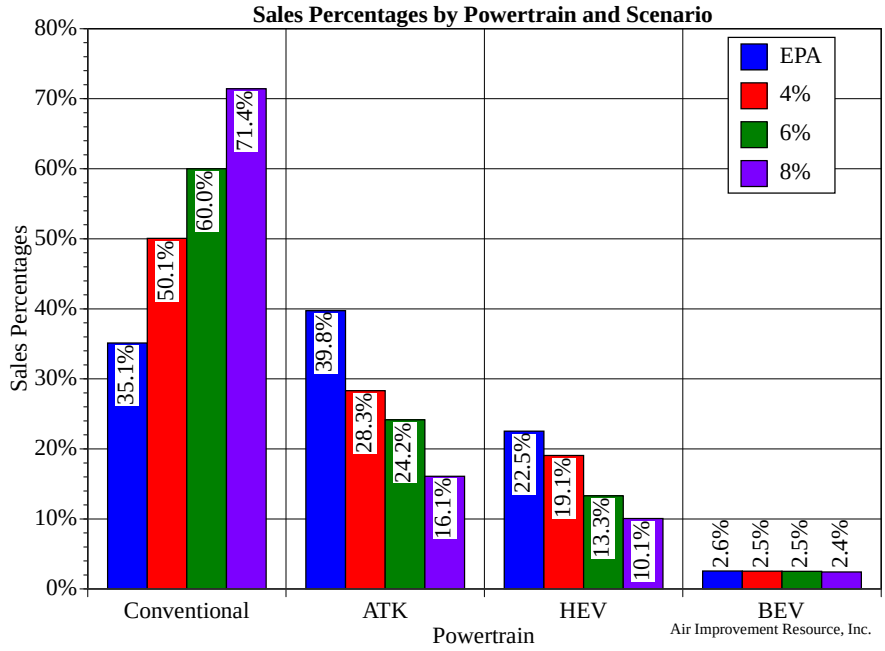


Figure 5

Sales Percentages by Powertrain and Scenario



6.0 Discussion

This analysis has shown that if a high octane mid-level blend ethanol fuel such as 98-RON E25 were an option for model year 2022-2025 vehicles meeting EPA's GHG standards, overall program costs would be significantly reduced. There is no doubt that if this fuel were to be made widely available to the public, auto manufacturers would certify vehicles using it.

Major inputs to this conclusion are (1) the magnitude of GHG emission reduction due to increased octane, (2) the cost of higher compression ratio plus the incremental cost (or savings) from the fuel, and (3) how implementing high HCR would affect the benefits of other types of technologies.

We have estimated the tailpipe GHG emission reduction due to higher compression engines for the central case at 6%. This effectiveness is somewhat higher than most other technologies estimated by EPA, but it is not out of line, and in fact could perhaps be considerably higher. There is a significant amount of research currently being done to refine this estimate, and the type of fuel needed to obtain as much engine efficiency improvement as practical. Our cost for the increased compression ratio of $100 also does not appear out of line, as some manufacturers have indicated it could be much less if done as a part of normal engine redesign cycles. Our analysis of fuel costs indicates that the fuel could be provided for slightly less than the current cost of regular. At this point, we are not sure how implementing HCR would affect the benefits of some of the other technologies, but more work will probably be performed on this as well.

Finally, another significant benefit of implementing a high-octane ethanol fuel with high compression ratio engines is that biofuel use would grow more significantly from today's levels, thereby reducing upstream GHG emissions from transportation fuels, growing the GHG benefits of the Renewable Fuel Standard, and reducing US petroleum consumption. Thus, the overall GHG benefits of EPA's 2022-2025 GHG standards with a high-octane low carbon fuel would be significantly greater than without a high-octane low carbon fuel.

Attachment 1

Detailed Technology Packages for the First 11 Tech Packages for the 2025 Buick Enclave

TP	Aero1	Aero2	ATK2	Deac-V6	DI	EFR1	EFR2	EGR	EPS	I4	IACC1	IACC2	LDB	LRRT1	LRRT2	LUB	MHEV48V	SAX-NA	Stop-Start
0					DI	EFR1										LUB		SAX-NA	
1	Aero1				DI	EFR1			EPS		IACC1		LDB	LRRT1		LUB		SAX-NA	
2	Aero1				DI	EFR1			EPS		IACC1		LDB	LRRT1		LUB		SAX-NA	
3	Aero1				DI		EFR2		EPS	I4	IACC1		LDB		LRRT2			SAX-NA	
4		Aero2			DI		EFR2		EPS	I4		IACC2	LDB		LRRT2			SAX-NA	
5		Aero2			DI		EFR2	EGR	EPS	I4		IACC2	LDB		LRRT2			SAX-NA	
6		Aero2			DI		EFR2		EPS	I4		IACC2	LDB		LRRT2			SAX-NA	
7		Aero2			DI		EFR2		EPS	I4		IACC2	LDB		LRRT2			SAX-NA	Stop-Start
8		Aero2	ATK2	Deac-V6	DI		EFR2	EGR	EPS			IACC2	LDB		LRRT2			SAX-NA	Stop-Start
9		Aero2			DI		EFR2		EPS	I4		IACC2	LDB		LRRT2		MHEV48V	SAX-NA	
10		Aero2			DI		EFR2	EGR	EPS	I4		IACC2	LDB		LRRT2		MHEV48V	SAX-NA	
11		Aero2	ATK2	Deac-V6	DI		EFR2	EGR	EPS			IACC2	LDB		LRRT2			SAX-NA	Stop-Start

TP	TRX11	TRX21	TRX22	TURB18	TURB24	V6	VVLTD-OHC-I4	VVT	WRnet- 1.5	WRnet- 2.5	WRnet- 5.0	WRpen- 0.0	WRpen- 2.5	WRtech- 1.5	WRtech- 5.0
0	TRX11					V6		VVT	WRnet- 1.5			WRpen- 0.0		WRtech- 1.5	
1	TRX11					V6		VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
2		TRX21				V6		VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
3		TRX21		TURB18				VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
4		TRX21		TURB18				VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
5		TRX21			TURB24			VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
6			TRX22	TURB18				VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
7			TRX22	TURB18				VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
8		TRX21				V6		VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0
9			TRX22	TURB18			VVLTD-OHC-I4	VVT		WRnet- 2.5			WRpen- 2.5		WRtech- 5.0
10			TRX22		TURB24			VVT		WRnet- 2.5			WRpen- 2.5		WRtech- 5.0
11			TRX22			V6		VVT			WRnet- 5.0	WRpen- 0.0			WRtech- 5.0

Abbreviation	Description	Abbreviation	Description
Aero1	Aero – passive	SAX-NA	Secondary axle disconnect; Not Applicable
Aero2	Aero – passive with active	Stop-Start	Stop-start without electrification
ATK2	Atkinson-2	TRX11	Transmission – step 1 or current generation
Deac-V6	Cylinder deactivation V6 engine	TRX21	Transmission – step 2 or TRX11 but with additional gear-ratio spread
DI	Gasoline direct injection	TRX22	TRX21 with improved efficiency
EFR1	Engine friction reduction level 1	TURB18	Turbocharging at 18/21 bar
EFR2	Engine friction reduction level 2	TURB24	Turbocharging at 24 bar
EGR	Cooled exhaust gas recirculation	V6	V-shaped 6-cylinder engine
EPS	Electric power steering	VVLTD-OHC-I4	Discrete variable valve lift and timing on an overhead cam I4
I4	Inline 4-cylinder engine	VVT	Variable valve timing
IACC1	Improved accessories level 1	WRnet- 1.5	Weight reduction, net, 1.5%
IACC2	Improved accessories level 2	WRnet- 2.5	Weight reduction, net, 2.5%
LDB	Low drag brakes	WRnet- 5.0	Weight reduction, net, 5.0%
LRRT1	Lower rolling resistance tires level 1	WRpen- 0.0	Weight reduction, penetration, 0.0%
LRRT2	Lower rolling resistance tires level 2	WRpen- 2.5	Weight reduction, penetration, 2.5%
LUB	Engine changes to accommodate low friction lubes	WRtech- 1.5	Weight reduction, technology, 1.5%
MHEV48V	Mild hybrid 48V	WRtech- 5.0	Weight reduction, technology, 5.0%

About the Authors

Mr. Thomas Darlington is President of Air Improvement Resource, a company formed in 1994 specializing in mobile source emission modeling. He is an internationally recognized expert in mobile source emissions modeling. He has evaluated the emission benefits and cost effectiveness of nearly every major on-road and off-road regulation proposed and adopted since 1988 in the U.S. and Canada. He has also reviewed and commented on the all of the emission models developed by the EPA and the California Air Resources Board in the 1990s. He has been called upon to testify on such regulations at EPA workshops and hearings, and at ARB workshops and Board Hearings in Sacramento, California. He has also reviewed EPA's Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS). He critically reviewed both Agencies' lifecycle analyses of corn ethanol, sorghum ethanol and palm oil biodiesel, including multiple reviews of changing indirect land use emissions. He prepares applications for biofuel companies for the LCFS and the RFS.

Mr. Dennis Kahlbaum is an expert in meteorology, computer programming, statistical and data analysis, graphical presentation, and geographical information systems (GIS). To assist with the requests of AIR's clientele, he has created special versions of the on-highway and off-highway emission and fuel consumption models in use by both the EPA and California Air Resources Board (CARB), including MOVES, MOBILE6, NONROAD, OFFROAD, and M6FCM. He has also executed and modified the GTAP6, GTAP7, FASOM, GREET, CCLUB, and AEZ-EF models to estimate the land use change (LUC) and greenhouse gas (GHG) emissions resulting from the EPA Renewable Fuels Standards (RFS) and CARB Low Carbon Fuel Standards (LCFS). Mr. Kahlbaum also maintains and performs all of the analyses of AIR's extensive ambient air and fuel quality databases. He provides meteorological, instrumentation, and data analysis support for Entergy's Palisades Nuclear Plant. In 1995, he was awarded the John Capanius Holm Award by the U. S. Dept. of Commerce, National Oceanic and Atmospheric Administration, which is the highest civilian honor given in recognition of co-operative observational meteorologists.

ATTACHMENT B

Comments of the Renewable Fuels Association re: Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation (Docket ID No. EPA-HQ-OAR-2015-0827)

RENEWABLE FUELS ASSOCIATION

December 30, 2016

Attention: Docket ID No. EPA-HQ-OAR-2015-0827

U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW
Washington, DC 20460

RE: Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation (Docket ID No. EPA-HQ-OAR-2015-0827)

Dear Administrator McCarthy:

The Renewable Fuels Association (RFA) appreciates the opportunity to comment on the above referenced Proposed Determination.

RFA is the leading trade association for America's ethanol industry. Its mission is to advance the development, production and use of fuel ethanol by strengthening America's ethanol industry and raising awareness about the benefits of renewable fuels. Founded in 1981, RFA serves as the premier meeting ground for industry leaders and supporters. RFA's 300-plus members are working to help America become cleaner, safer, more energy secure, and economically vibrant.

In short, we were surprised and disappointed that the Proposed Determination was issued so quickly after the close of the comment period on the Draft Technical Assessment Report (TAR). We are troubled by the fact that the Proposed Determination fails to take into account many of the comments and recommendations submitted by affected stakeholders in response to the Draft TAR. More specifically, we are greatly concerned that, to date, the Midterm Evaluation (MTE) process has focused exclusively on vehicle and engine technologies in the 2022-2025 timeframe and has largely ignored the influence of fuel parameters (like octane rating) on fuel economy and GHG emissions.

RFA and many other stakeholders provided detailed technical comments in response to the Draft TAR's evaluation of the appropriateness of the Model Year 2022-2025 standards. We are concerned that our comments and recommendations likely were not reviewed as intensively as is warranted for a ruling that will have important consequences for the transportation and fuels industries over the coming years. Attached to this letter, we are again enclosing our comments responding to the Draft TAR; we encourage EPA to give our comments (and the submissions of other stakeholders) careful consideration before issuing a Final Determination. Furthermore, we recommend that EPA and NHTSA retain the original schedule for release of the Final Determination (i.e., April 2018); this would ensure adequate time for the agencies to fully review and incorporate the feedback received from stakeholders in response to the Draft TAR and Proposed Determination.

Our concerns with the Draft TAR are extensive, and these issues were left unaddressed in the Proposed Determination. As outlined more fully in the attached comments, our most critical concerns with the MTE process to date include the following:

- Many of the advanced internal combustion (IC) engine technologies examined in the TAR and Proposed Determination Technical Support Document (TSD) implicitly call for liquid fuels with higher octane than is offered by today's regular gasoline.
- While the TAR and TSD examine various advanced IC engine technologies, they fail to simultaneously examine the fuels that *enable* those engine technologies. In general, the TAR and TSD fail to treat IC engines and liquid fuels as integrated systems, even though fuel properties can have significant effects on fuel economy and emissions.
- The TAR and TSD ignore the influence on fuels of other public policies, like the Renewable Fuel Standard (RFS), aimed at reducing petroleum consumption and GHG emissions.
- Pairing the advanced IC engine technologies examined in the TAR and TSD with high octane low carbon (HOLC) fuels with 98-100 RON octane would result in greater fuel economy and emissions benefits than considered by EPA and NHTSA.
- Use of an ethanol-based HOLC in optimized IC engines would be the lowest cost means of achieving compliance with CAFE and GHG standards for MY2022-2025 and beyond.

As underscored in the attached comments, consensus is building around the need for HOLC fuels to enable greater engine efficiency and reduce emissions. Published research has clearly demonstrated that HOLC fuels would enable high compression ratio engines and other advanced IC technologies, which would in turn improve engine efficiency and reduce emissions.

The EPA clearly has authority to regulate fuel parameters that effect emissions, and thus the Agency should use the MTE process to introduce regulations that specify minimum octane ratings that will reduce emissions of CO2 and other pollutants and simultaneously facilitate greater fuel efficiency. RFA believes that adoption of new regulations governing octane levels could be done fairly quickly, and that the MTE should include the regulatory roadmap that the agencies, automakers and other stakeholders can follow to assure that gasoline in 2025 and beyond has the minimum octane rating required to enable proliferation of advanced IC engine technologies that improve fuel efficiency and slash automotive emissions.

Thank you again for the opportunity to comment and we look forward to interacting further with EPA throughout the MTE process.

Sincerely,

Bob Dinneen
President & CEO

Attachment: *Comments of the Renewable Fuels Association (RFA) in response to Notice of Availability of Midterm Evaluation Draft Technical Assessment Report for Model Year 2022–2025 Light Duty Vehicle GHG Emissions and CAFE Standards (81 Fed. Reg. 49,217; July 27, 2016)*

ATTACHMENT C

Literature Review of Ethanol Use for High Octane Fuels: Final Report. Ricardo, Inc. Prepared for Renewable Fuels Association. (August 23, 2017)

August 23, 2017

LITERATURE REVIEW OF ETHANOL USE FOR HIGH OCTANE FUELS

FINAL REPORT

Prepared for:

Renewable Fuels Association
425 3rd Street
Washington DC, 20024

Prepared by:

Ricardo, Inc.
40000 Ricardo Dr.
Van Buren Twp., MI 48111

Ricardo Project Number:
C015568

Date issued:
August 22, 2017

REVISION HISTORY

Revision	Date	Section #s Affected	Changes Made	Changed By
1	June 13, 2017	all	First issue	DLB2
2	August 22, 2017	all	Updated	MSK

EXECUTIVE SUMMARY

A literature review was performed to provide an objective view of the existing body of research regarding the use of ethanol to produce high octane gasolines in the US and the impact of high octane fuels on modern spark-ignited engine efficiency. The review found that ethanol has several innate characteristics that make it amenable to increasing the compression ratio and therefore the efficiency of modern spark-ignited engines. Ethanol has lower energy content than gasoline on a per-gallon basis. However, when ethanol is splash blended to increase the octane rating of the finished gasoline, and advantage is taken of the higher octane by increasing the compression ratio of the engine, mid-level ethanol blends can offer similar fuel economy and driving range as gasoline.

High octane, mid-level blends of ethanol ranging from 15-40% by volume are seen as offering the best trade-off between greenhouse gas (GHG) benefits and ease of implementation of fuel dispensing to achieve widespread availability. The National Renewal Energy Laboratory (NREL) concluded that since the UL already has a certification class for E25 dispensing equipment that is similar in price to E10 equipment, it would be the easiest to deploy and least costly of the high octane fuels.

Ethanol is known to have a high octane rating of approximately 108 research octane number (RON), giving it a high resistance to engine knock. For comparison, regular grade E10 gasoline has RON values typically around 92 for most of the US. What is less well-known, however, is that ethanol also has high sensitivity, meaning that in today's high power density engines, which often run with retarded combustion timing, the performance level can be extended to a greater degree than is indicated by RON alone. Ethanol also has a heat of vaporization that is almost four times higher than gasoline when compared on a stoichiometric combustion air basis. This means that in direct injection engines, there is a charge cooling effect giving ethanol a "cooling octane number" that is additive to it's chemical octane rating. The energy density of ethanol, on the other hand, is lower than that of gasoline on a volumetric basis so that one gallon of E85 fuel typically has about the same energy as 0.75 gallons of gasoline without any ethanol.

Numerous studies and technical papers from a wide variety of sources were examined for this literature review. A detailed bibliography of the studies reviewed is included with this report. The results from the studies reviewed generally support a main conclusion that splash blending ethanol is a highly effective means of raising the octane rating of gasoline and enabling low-cost efficiencies and reduced emissions in modern spark-ignition engines. For example, one study from an authoritative group of Original Equipment Manufacturers (OEM) scientists found that compression ratio increases leading to efficiency improvements of 5% for DI boosted gasoline engines could result from increasing the octane rating to 98 RON with 25% ethanol fuel. On the subject of emissions

impacts, one study noted GHG reductions of 6 – 9% depending on driving behavior with 98-RON E30 fuel at equal performance levels in engines having compression ratio raised from 10:1 to 13:1. On the economics of high octane fuels, one study found that the refinery cost of increasing octane to 98 RON from 93 RON is only $0.02/gallon when ethanol is used as the means of increasing octane rating; however, the cost is $0.20 gallon when hydrocarbon octane sources are used. Finally, one group used EPA's OMEGA tool for modeling the costs of achieving GHG standards for the 2025 model year and found that by adopting a 98 RON E25 fuel standard and increasing engine efficiency could result in a national cost savings of $7B or a per vehicle savings of $436 over continued use of regular E10 gasoline.

TABLE OF CONTENTS

LITERATURE REVIEW OF ETHANOL USE FOR HIGH OCTANE FUELS

1 INTRODUCTION

The Renewable Fuels Association (RFA) has requested Ricardo to provide an objective review of the existing body of research concerning the technical merits of using ethanol as a blendstock to increase the octane rating of gasoline motor fuels sold in the United States. Furthermore, the Association is seeking a review of literature that examines how modern engine efficiency is impacted by the properties of ethanol-gasoline blends including the fuel's octane rating, the heat of vaporization and the sensitivity of the fuel or the difference between it's research octane number (RON) and motor octane number (MON).

Ricardo will expand upon and update the review that was performed last year in preparation for the RFA to submit comments on the EPA's Technical Assessment Report. This report embodies a new objective literature review articulating the technical issues regarding renewable fuels use in spark-ignited engines and motor vehicles. The report will examine in particular the effects on engine efficiency and performance through varying the fuel anti-knock index (RON + MON)/2, sensitivity (RON – MON) and the heat of vaporization.

2 APPROACHES TO IMPROVING VEHICLE FUEL ECONOMY AND ENGINE EFFICIENCY

Two main solution pathways to improving vehicle fuel economy and reducing CO_2 emissions have been outlined as the dominant approaches worldwide in recent years:

- High-efficiency naturally-aspirated engines utilizing high compression ratio, modified inlet valve closing strategies, and/or cooled exhaust gas recirculation, for high efficiency at lower specific rating
- Highly-boosted, downsized engines for part-load efficiency with relatively high specific rating

The Magma concept described by Osborne (Osborne, et al. 2017) represents an attempt to combine high compression ratio and advanced valve-timing strategy with downsizing and boosting in a Miller cycle with advanced boosting strategies to obtain greater efficiency benefits without compromising full-load performance.

Another main solution pathway is the hybridization of conventional internal combustion engines. This approach to improving vehicle and engine efficiency starts with simple engine start/stop strategies to reduce the amount of time the engine is idling and increases the amount of electric assist in an attempt to reduce the amount of time the engine is running

at low loads and make a shift towards operation at or near its peak efficiency point. Another added benefit of electrification is the ability to recapture the vehicle's kinetic energy instead of wasting it producing heat. The hybridization approach is often combined with the first main approach of increasing the efficiency of naturally-aspirated engines by increasing the compression ratio and modifying the inlet valve closing event to minimize the pumping work at the lower loads, often called Atkinson cycle. In recent years, Atkinson cycle engines have also been implemented in non-hybrid vehicles, albeit with not as great an increase in compression ratio nor modification of inlet valve closing timing, such as the Mazda Atkinson-cycle engine (Weissler 2011).

One more solution pathway to increasing efficiency is variable compression ratio, wherein the engine operates at high compression ratio at lower loads and switches to a lower compression ratio when high loads are called for. Variable compression ratio (VCR) has been researched for years (Boretti, Scalzo and Masudi 2011) with many different mechanisms being investigated but has only recently been developed to the point of production-intent by Nissan Motor Co. (INFINITI 2017), (autoblog 2016). The fuel economy benefits of 2-step and continuously variable VCR was examined by Shelby (Shelby 2017). The study estimated a 2-step VCR fuel economy benefit of 2.5-3.1% on the EPA metro-highway (M-H) drive cycle and 0.8-1.2% on the US06 cycle relative to a fixed 10:1 compression ratio engine. The benefit levels increased slightly for continuously variable VCR compared to 2-step to 2.7-3.3% on the M-H and more significantly on the US06 to 1.7-2.1%.

There are two key, fundamental mechanisms being addressed by the solution pathways outlined above: firstly, the compression ratio which at the most basic level controls the overall thermodynamic effiency of an engine cycle and secondly, the parasitic losses in an engine which limit the amount of useful shaft power that can be produced from the conversion of the fuel's energy into heat. The parasitic losses can be further broken down into mechanical friction and pumping loss or engine breathing losses. Mechanical friction is mainly dependent on engine speed but pumping losses are mainly dependent upon engine load with higher losses being incurred at lower loads due to throttling as the primary means for controlling engine load in a spark-ignited (SI) engine. Pumping losses can be minimized through either early intake valve closure (EIVC) or late intake valve closure (LIVC) approaches for stoichiometric engines or by lean operation. There are challenges to keeping emissions in check with lean combustion systems and these approaches require lean NOx aftertreatment; nonetheless these technologies are showing promise in also achieving cost reductions as they continue to be developed.

The optimal intake valve closure strategy has also been the subject of debate and research for some time (Boggs, Hilbert and Schechter 1995) with various outcomes depending on

whether it is applied to a naturally-aspirated or a boosted engine (Ferrey, et al. 2014). Comparisons between EIVC and LIVC have recently been made experimentally on an SI engine with the EIVC strategy showing slightly greater potential to improve engine efficiency at part-load conditions, although both approaches were better than the conventional throttled approach (Lanzanova, Nora and Zhao 2017). The major drawback of the EIVC strategy was longer combustion duration, and it is for this reason that Osborne et al. use a modified intake port to enhance the tumble motion when adopting the EIVC strategy for the Magma concept.

3 LIMITATIONS ON EFFICIENCY IMPROVEMENT

There are practical limitations to improving the efficiency of modern gasoline engines that fall into two categories: structural limitations and end-user acceptability limits. Structural limitations define the peak pressures within the cylinder and maximum material temperatures that can be tolerated. There are also limitations that come about from a vehicle user's desire for comfort, namely the noise, vibration and harshness (NVH) experienced in the vehicle. These vehicle characteristics have been translated into engineering requirements on the engine in the form of limits on the rate of pressure rise and on the variation of average pressure over an engine cycle. Rate of pressure rise impacts the sound quality and harshness of sound that is emanating from the engine and the variation of average pressure has to do with the lower frequency vibrations that are transmitted through the vehicle structure and felt by the driver. Rate of pressure rise will be discussed more in the section on engine knock.

The average pressure over an engine cycle is known as the mean effective pressure (MEP) and is used as a measure of the work produced per cycle. Variation of MEP represents the variation in work output from cycle to cycle and the coefficient of variation (COV) is therefore a measure of variability of work produced expressed as a percentage of the average work per cycle. The COV of IMEP then is used as a measure of the variation of work output or strength of combustion. The "I" before MEP simply means that it is *indicated* from the cylinder pressure diagram and is the maximum work that can be done by the combustion pressures acting on the piston top before friction and pumping losses are subtracted.

There are two ways of expressing the IMEP for a 4-stroke engine: gross IMEP and net IMEP. Gross IMEP is calculated as the mean cylinder pressure averaged over all four strokes of the cycle including the intake and exhaust breathing strokes; net IMEP, or NMEP for short, is the mean pressure calculated only over the compression and expansion strokes of a combustion cycle, and is therefore a purer measure of the work obtained from combustion without reference to the intake and exhaust strokes. For this reason the COV of IMEP is

sometimes referred to as "combustion variability." In either case, variation in IMEP is a key component of the forcing function for the vibrations that are felt in a vehicle and are especially noticeable at idle conditions where the average IMEP is small. Limits are set during engine testing programs for the COV of IMEP at 3% or less typically which represents an acceptable level of combustion variation that is derived from studies of what drivers perceive as tolerable levels of vibration within a vehicle.

3.1 Engine Knock

The most common phenomenon limiting gasoline engine performance and efficiency is commonly known as knock which tests all of the limiting design factors and can result in severe engine damage if not properly controlled. The engine structure can be stressed well-beyond design limits due to the very high cylinder pressures that are created with severe knock. The fact that knock is a very fast, localized heat release means that pressure waves are generated and can lead to very high heat transfer rates from the scrubbing action of the waves raising combustion chamber surface temperatures if it is prolonged. The fast heat release gives rise to pressure waves in the cylinder that are in the audible frequency range which excite the engine structure with a characteristic knocking sound. The audible knocking frequency range is much higher (as shown below by Naber (Naber, et al. 2006) in the section on knock measurement) than the low frequency COV of IMEP variations described above which are felt as vibrations in a vehicle.

The theory behind knock was described by Draper (Draper 1933) in a NACA report as follows: "If a firecracker is exploded inside a closed drum containing air, two effects naturally follow: A series of sound waves is set up by the sudden local increase in pressure at the explosion and the general pressure within the drum rises because of the energy liberated. The frequency of the resulting sound waves will depend on the dimensions of the drum, the air pressure, and the position of the firecracker within the drum. It is reasonable to suppose that the process known as detonation in internal-combustion engines is similar to that taking place in the case outlined above." Draper further developed the theory of knock in order to quantify its characteristics as illustrated in Figure 1.

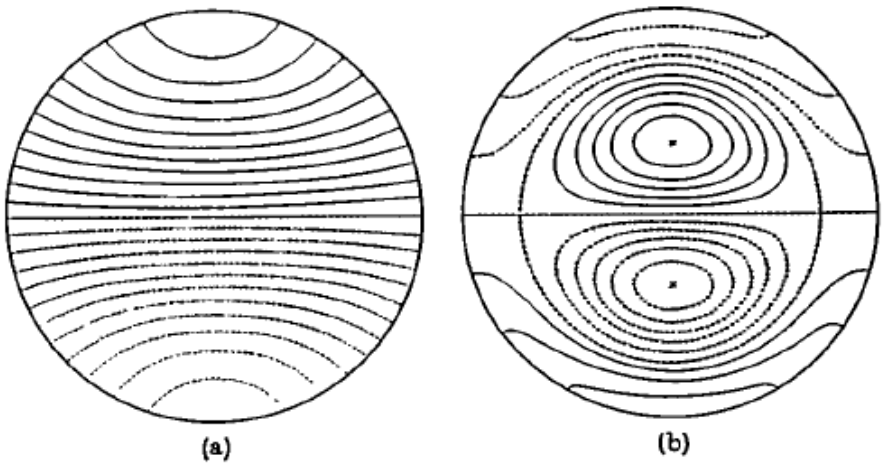


FIGURE 3.—Lines of constant pressure for two transverse modes of vibration in circular cylinder: (*a*) Single nodal plane; (*b*) one nodal cylinder in addition to nodal plane.

FIGURE 1 PRESSURE WAVE PATTERNS IN A CYLINDER AS DESCRIBED BY DRAPER

Heywood (Heywood 1988, 462) described knock as emanating from "autoignition of the fuel-air mixture in the end-gas. *Autoignition* is the term used for a rapid combustion reaction which is not initiated by any external ignition source." Naber have used both cylinder pressure transducers and accelerometers mounted on an engine block to compare alternative ways of measuring and controlling knock. Figure 2 compares the cylinder pressure traces and the band-pass filtered signals (5-27 kHz) which were used to determine knock intensity. The frequencies of the filtered pressure signals correlates well with the modes of vibration originally developed by Draper. The knocking intensity was also quantified by Naber's measurements and expressed as a pressure intensity for the amplitude of the filtered pressure signal or an accelerometer intensity based on the filtered accelerometer signal.

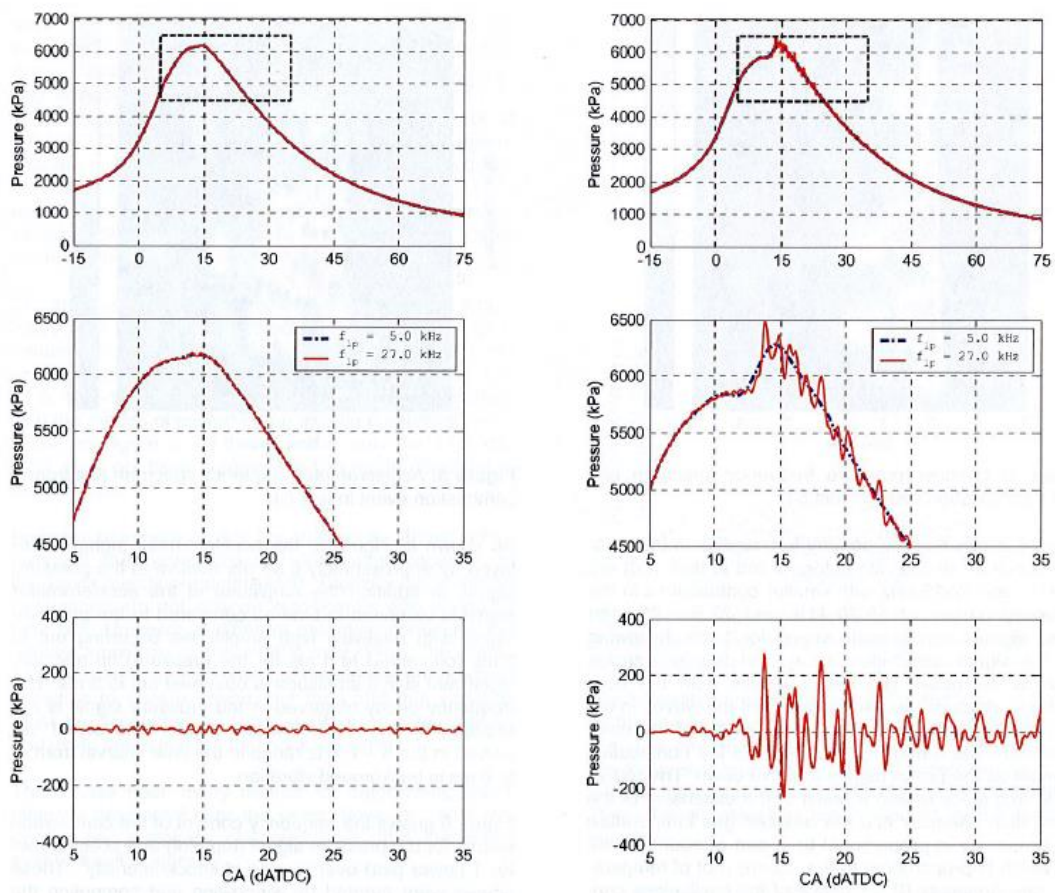


Figure 2: Cylinder pressure (C4) for a non-knocking combustion event in test 54.

Figure 3: Cylinder pressure (C4) for a knocking combustion event in test 54.

FIGURE 2 CYLINDER PRESSURE TRACES FROM NON-KNOCKING (LEFT) AND KNOCKING (RIGHT) COMBUSTION EVENTS. (FROM NABER)

3.2 Low-speed pre-ignition and mega-knock

Low-speed pre-ignition (LSPI) is another phenomenon related to to knock and occurs when enough heat is released before the spark can initiate a normal combustion event. LSPI can lead to mega-knock that can quickly destroy an engine; the results of low-speed pre-ignition and mega-knock can be seen in the piston damage shown in Figure 3 from Mayer (Mayer, Hofmann and Williams, et al. 2016a)

FIGURE 3 PISTON DAMAGE OCCURRING AS THE RESULT OF LOW-SPEED PRE-IGNITION LEADING TO MEGA-KNOCK (FROM MAYER, 2016A)

The pre-ignition event, deflagration of the flame that was initiated by the spark, and mega-knock are all apparent in the pressure diagrams shown in Figure 4. There are multiple causes for LSPI such as detached combustion chamber deposits or hot residual gas but this work undertakes developing a methodology to verify only oil induced pre-ignitions. Mayer, 2016a clearly demonstrates that calcium detergent additives in engine oils were able to induce self ignitions whereas magnesium detergents failed to reach its critical temperature, as shown in Figure 5.

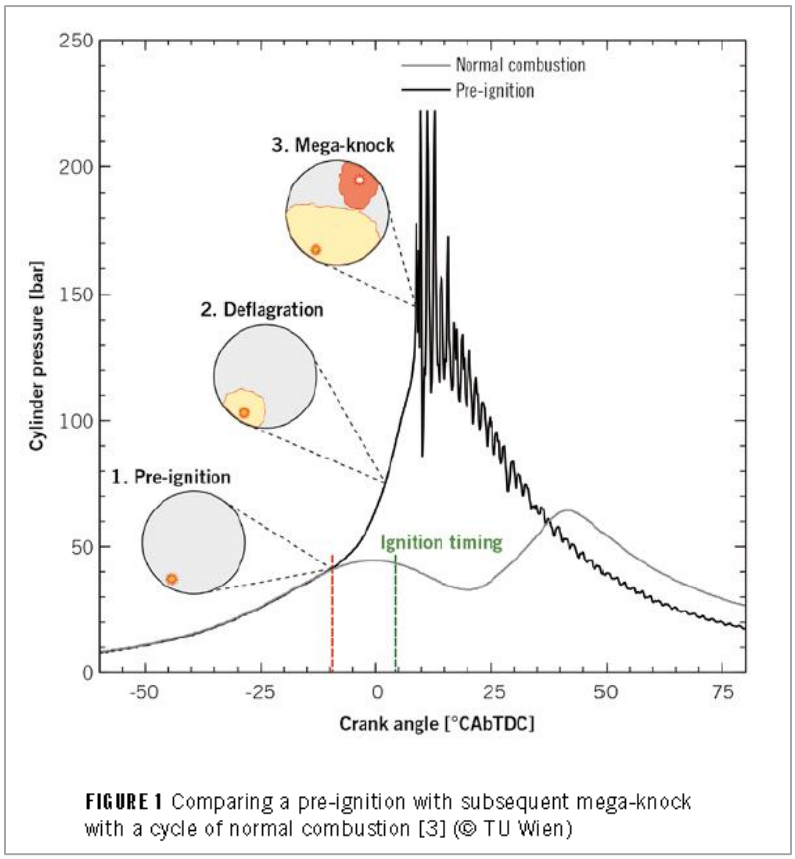


FIGURE 4 PRE-IGNITION LEADING TO MEGA-KNOCK AS SHOWN BY MAYER, 2016A

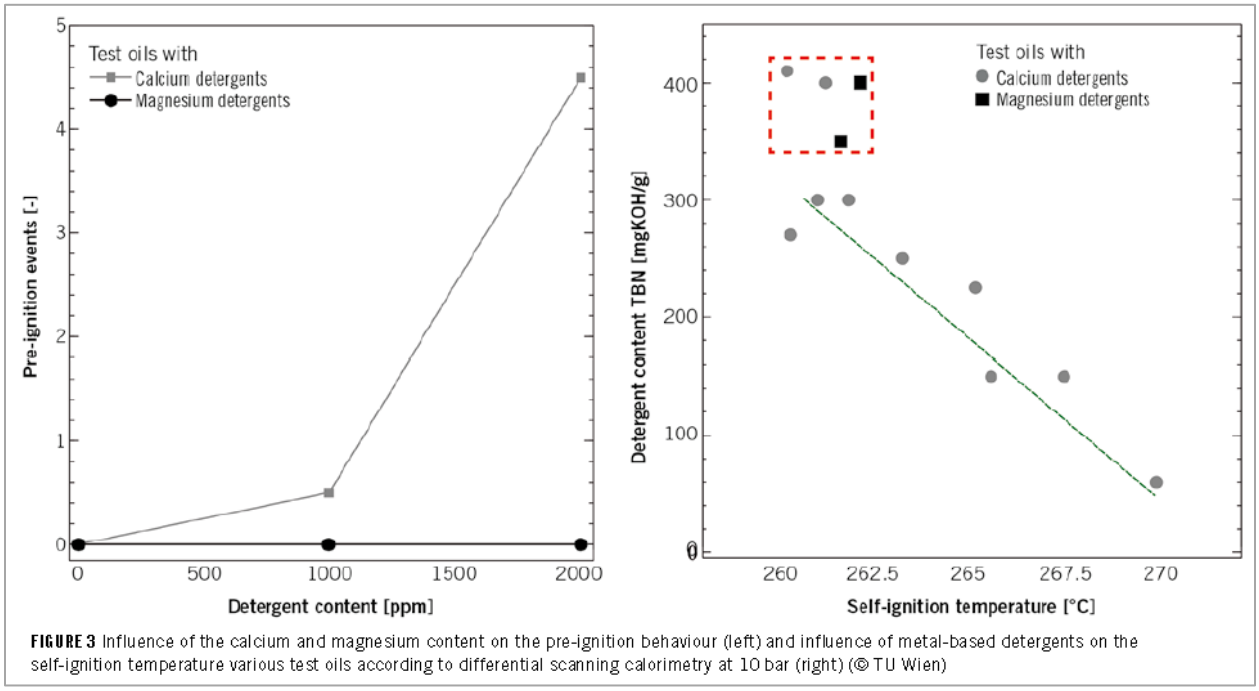


FIGURE 5 PRE-IGNITIONS CAUSED BY CALCIUM DETERGENTS BUT NOT BY MAGNESIUM DETERGENTS (FROM MAYER, 2016A)

In a study on using enrichment with a DI injector with charge cooling to suppress very heavy knock levels (up to 40 bar), a trade-off was observed in which knock intensity first increased by up to 60% before lower unburned gas temperatures suppressed knock under extremely rich conditions (vafamehr, Cairns and Moslemin Koupaie 2017). Such a trade-off is not usually observed in low-to-moderate knock intensity situations. The trade-off was associated with reducing auto-ignition delay times outweighing increasing charge cooling and ratio of specific heats. Ethanol was seen to be more effective than other fuels in reducing knock intensity. Overall, the results demonstrate the risks in employing excess fuel to suppress knock deep within a heavily knocking combustion regime (potentially including a super-knock regime).

3.3 Testing limits imposed by knock

The limitations on efficiency improvement, both structural and user acceptability limits, have been well understood and translated into engine-specific engineering criteria so that engines can be tested in a repeatable manner on an engine dynamometer. Test procedures have been applied to determine the peak torque that can be achieved from an engine using different fuels. The basis of these test procedures is to identify the borderline knocking condition, that is the engine operating conditions where knock first becomes robustly detectable; an engine is operating at knock-limited conditions when borderline knock is detected. Test procedures such as these have been rigorously applied and are described in the following description adapted from Stein et al (Stein, Polovina, et al. 2012).

Starting from a low load point and as inlet pressure and NMEP are increased, the engine becomes more knock-limited and spark timing must be retarded. As NMEP increases and combustion phasing is retarded, the exhaust temperature increases both due to the higher load, which reduces heat transfer per unit mass, and due to degraded efficiency, which results in increased energy in the exhaust gas. When exhaust gas temperature reaches its limit, lambda (defined as the air-fuel ratio divided by the stoichiometric air-fuel ratio) must be enriched to control exhaust temperature. Although turbocharged SI engines typically have a 950°C turbine inlet temperature limit, it was found from experience that an exhaust temperature of 850°C on the single cylinder engine used in these tests corresponded to a multi-cylinder engine exhaust temperature of 950°C. Finally, as inlet pressure and NMEP are further increased, the peak cylinder pressure can also increase, depending on the amount of combustion phasing retard. Once the peak cylinder pressure reaches the engine's structural limit, the spark timing must be retarded. A load sweep wherein these test procedures were applied and the specific limits for each constraining parameter is illustrated in Figure 6. In the top graph CA50 indicates the crank angle (CA) where 50% of the fuel is burned, representing the mid-point of combustion, and was set at 30° aTDC (after top dead center) as combustion stability tends to become unstable beyond that. In

the third graph from the top lambda is ideally equal to 1.0, except as needed to protect the exhaust turbine.

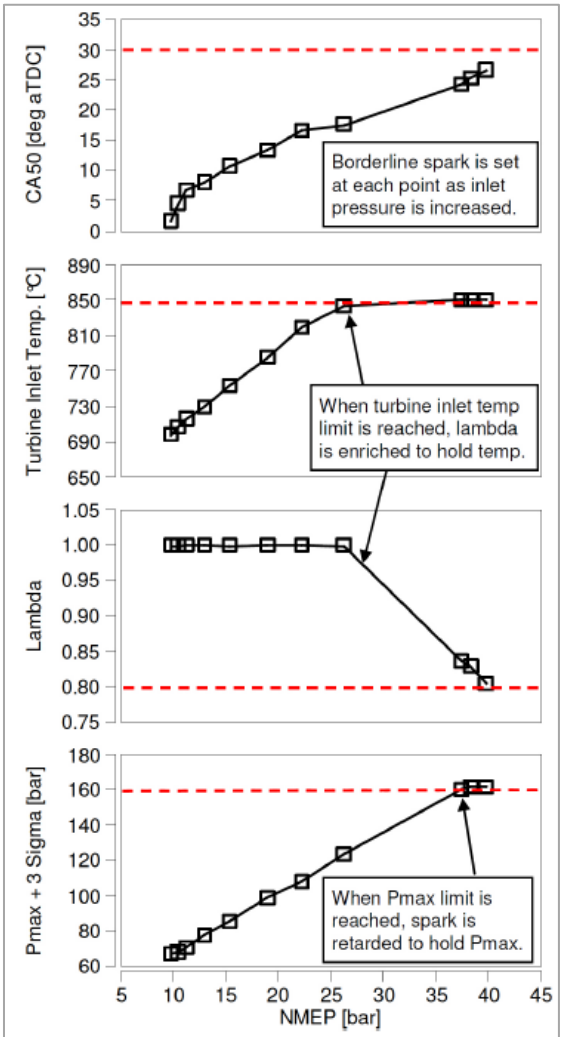


FIGURE 6 APPLICATION OF TEST PROCEDURES AND LIMITS ON ENGINE PERFORMANCE (FROM STEIN, 2012)

4 FUEL PROPERTIES

4.1 Octane and anti-knock ratings

Because engine knock is such a dominant factor in limiting the efficiency and performance of modern gasoline engines, it is important to understand the characteristics of fuels as they strongly influence the knocking tendency of SI engines. The tendency of gasoline fuels to resist knocking in an engine is known as the octane number. "Octane number is not a single-valued quantity and may vary considerably depending on engine design, operating

conditions …, ambient weather conditions …, mechanical condition of engine, and type of oil and fuel used in past operation. …Several octane rating methods have been developed. Two of these - the research method (ASTM D-2699)[1] and the motor method (ASTM D-2700) – are carried out in a standardized single-cylinder engine" (Heywood 1988, 471) under two specified sets of engine operating conditions giving a research octane number (RON) rating to a fuel, and a motor octane number (MON) rating to a fuel, respectively. The anti-knock index (AKI) then is the arithmetic average of the RON and MON numbers.

It is important to understand the engine operating conditions for the RON and MON tests so applicability to today's engines can be assessed. The RON and MON tests are both done in a variable compression ratio single-cylinder engine known as a "Cooperative Fuel Research (CFR™) engine manufactured by GE Energy Waukesha,"[2] (Stein, Polovina, et al. 2012) but at different inlet conditions, engine speeds and spark timings as shown in Table 1.

TABLE 1 FROM STEIN, 2012

Table 1. Engine conditions for the RON and MON tests.

Parameter	RON	MON
Inlet Air Temperature	52°C	38°C
Inlet Mixture Temperature	*	149°C
Intake Air Pressure	atmospheric	atmospheric
Coolant Temperature	100°C	100°C
Engine Speed	600 rpm	900 rpm
Spark Timing	13° bTDC	14 - 26° bTDC
Compression Ratio	4 - 18	4 - 18

**Not specified, but will be lower than the inlet air temperature.*

"Carburetion is used for fuel introduction in these tests. For the RON test, the inlet air temperature of 52°C is set upstream of the carburetor." (Stein, Polovina, et al. 2012) As a consequence the RON test more closely mimics the conditions of a port-injected engine where the fuel evaporation cools the fresh charge mixture in the intake port. "For the MON test, the inlet air-fuel mixture temperature of 149°C is set downstream of the carburetor." (Stein, Polovina, et al. 2012) Consequently the MON test does not include any of the charge cooling effect from the fuel evaporation. That is why "many published papers … indicate that the knock resistance of a fuel in modern engines more closely realtes to RON." (Stein, Polovina, et al. 2012) In direct injection (DI) engines, however, all of the fuel evaporation takes place within the cylinder, although much of the heat of vaporization may be picked up from the combustion chamber walls rather than the air charge for wall-guided injection

[1] ASTM denotes American Society for Testing and Materials; the letter and number defines the specific testing code.
[2] The CFR engine manufacturing rights have been owned by CFR Engines, Inc. since 2014.

systems. Regardless of the type of DI injection spray however, it is the cooling of the fresh air charge in the cylinder that enables an increase in the amount of charge that can be inducted and an increase in the resistance to knock.

Vertin (Vertin, et al. 2017) studied the effects of gasoline AKI at high altitude and found that vehicles operating with 85 AKI fuel showed strong evidence detected onset of knock earlier than when operating with 87 AKI fuel and used different engine control setting for knock avoidance. As a consequence they found all 5 of the tested vehicles showed some reduction in net power. Williams (Williams, et al. 2017) found that, for Euro 5 and Euro 6 passenger cars, the benefits of moving to higher octane fuel were about double on the US06 test cycle than those observed for the WLTC test cycle.

The octane index (OI) has been proposed as a better way to describe the anti-knock quality of gasolines in modern DI engines by Kalghatgi (Kalghatgi, Fuel/Engine Interactions 2013), (Kalghatgi, Head, et al. 2014) where

$$OI = (1 - K) * RON + K * MON$$

The fuel's sensitivity is the difference between its RON and MON ratings, or $S = RON - MON$, and the equation can be rewritten as

$$OI = RON - K * S$$

For downsized turbocharged engines running at higher torque levels, the values of K have been found to be negative; i.e. the anti-knock performance of a fuel increases proportionally with RON and with fuel sensitivity. However, Stein (Stein, 2012) noted the values of K depend on the operating conditions of the engine, the fuel system type, and the fuel's chemical knock resistance and heat of vaporization; K decreased with increasing evaporative charge cooling (e.g. as provided by DI fuel injection or higher ethanol concentration in the fuel) and with increasing combustion phasing retard, and K increased with increasing inlet temperature and increasing compression ratio. A recent study by Zhou (Zhou, et al. 2017) compared four different test methods for determining K. The value of K was found to be consistently negative at higher loads with DI. However, at part-load conditions, K was determined to approach 0.5.

4.2 Chemical octane and charge cooling effects

Recognizing not only the importance of a fuel's 'chemical' octane rating as expressed by its RON and its sensitivity, but also a fuel's heat of vaporization to further reduce the propensity to knock in DI engines, Stein, 2012 designed a set of experiments to cleanly separate the two effects. This was accomplished by comparing performance of a neat gasoline (E0) to an E50 blend made from the same 88 RON gasoline blendstock splash blended with 50 v% ethanol, first of all using an upstream fuel injection (UFI) system and

secondly with a DI injection system. Figure 7 shows the chemical octane effect by the difference between the red and green lines and the charge cooling effect by the difference between the blue and red lines. The chemical octane effect is seen by comparing the E50 blend to the E0 gasoline, with octane ratings of X and Y respectively, where both fuels were fully evaporated before entering the engine by UFI. The charge cooling effect is seen in this case by comparing the same E50 fuel as introduced directly into the cylinder, thereby utilizing the full heat of vaporization of the ethanol blend by DI injection for charge cooling, to introduction of the fuel upstream with UFI injection which has no charge cooling in-cylinder.

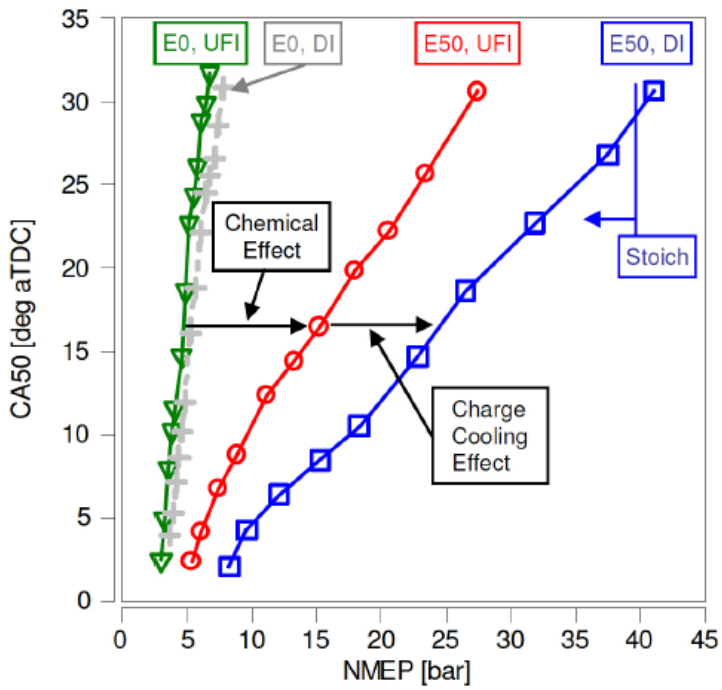


FIGURE 7 SEPARATION OF CHEMICAL OCTANE AND CHARGE COOLING EFFECTS (FROM STEIN, 2012)

As illustrated by the two black arrows at 16 deg aTDC CA50 timing, the maximum achievable NMEP at equal knock-limited combustion phasing increases from 5 bar to 15 bar solely due to the chemical octane increase and from 15 bar to 24 bar exclusively due to the influence of increased charge cooling.

4.3 Sensitivity to autoignition kinetics

A fuel's sensitivity (RON – MON) plays a profound role in its ability to resist knock and the anti-knock ability increases as combustion phasing is retarded from minimum spark advance for best torque (MBT). Mittal (Mittal, Heywood and Green 2010) explained that sensitivity is a measure of how much the autoignition kinetics of a fuel vary with the temperature of the unburned end gas, as shown in Figure 8. Note the logarithmic scale on

the y-axis to get a better sense of how much autoignition delay times can be impacted by temperature. Shorter delay times means the fuel-air mixture will reach it's critical autoignition point (i.e. knock) sooner. Figure 8 also shows conceptually how a high sensitivity fuel exhibits much longer autoignition delay times at low temperatures compared to a low sensitivity fuel and therefore a reduced tendency to knock. The conditions where high sensitivity fuels exhibit this tendency include the end gas temperatures in DI engines and turbocharged DI engines with retarded combustion phasing.

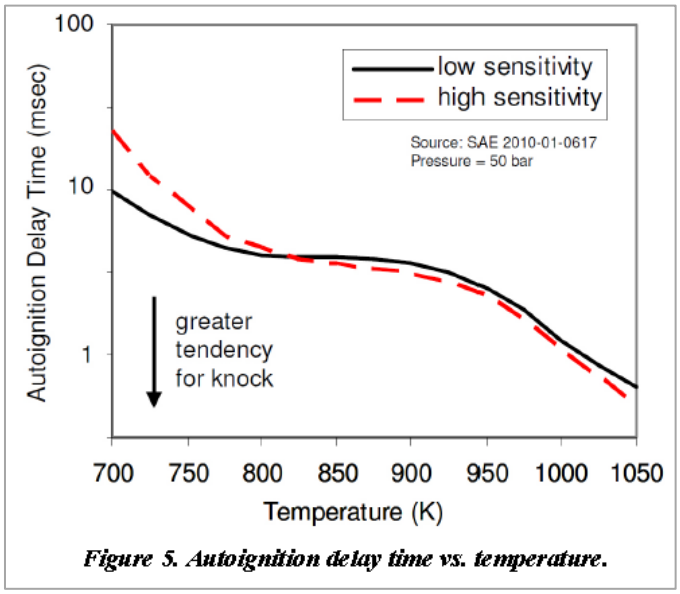


FIGURE 8 CONCEPTUAL ILLUSTRATION OF HIGH AND LOW SENSITIVITY FUELS KNOCKING TENDENCY (FROM STEIN, 2012)

The sensitivity of the fuels as ethanol is blended in increasing percentage is shown in Figure 9 with ethanol having a high sensitivity value greater than 15. As can be seen in Figure 7, above, the reduction in slope of the curves as combustion phasing (CA50) is retarded is due to the high sensitivity of the autoignition kinetics of ethanol to unburned gas temperature. The effect of ethanol's high sensitivity on the bending over of the CA50 vs NMEP curves is seen to a greater degree in Figure 10 with an E75 blend having an almost unlimited ability to resist knock as it's curves tend to level off at increasing NMEP levels while not having reached the 30° aTDC retard limit yet, except for the UFI case. Notice also how the E0 gasoline, with a much lower sensitivity, displays very little if any bending of it's curves.

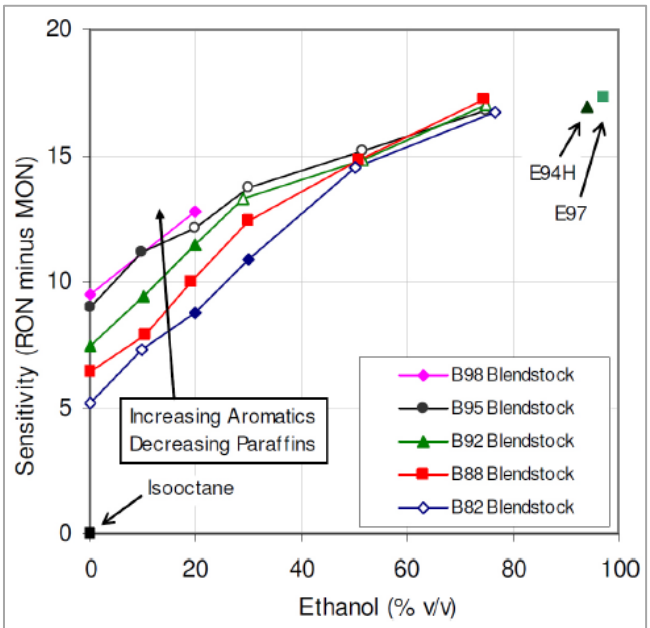


Figure 4. Sensitivity of test fuels (solid symbols denote engine testing and RON/MON measurement; open symbols denote RON/MON measurement only).

FIGURE 9 FUEL SENSITIVITY VS ETHANOL PERCENTAGE (FROM STEIN, 2012)

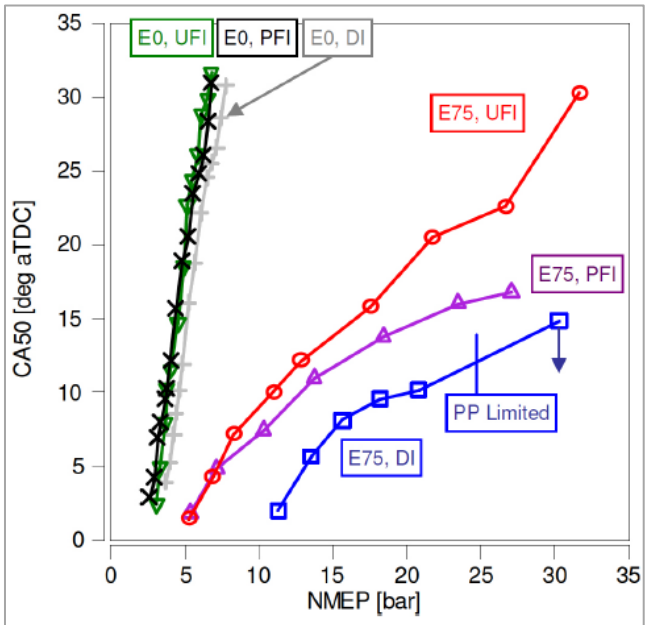


Figure 15. Comparison of CA50 vs. NMEP for UFI, PFI, and DI for B88E0-R88 and B88E75-R108 fuels at 10:1 CR and 1500 rpm.

FIGURE 10 COMBUSTION PHASING VS NMEP FOR E0 AND THE E75 BLEND SHOWS GREATER BENDING OF THE CURVES THAN E50 (FROM STEIN, 2012)

A recent study using only E10 blends from Shell Global Solutions (Prakash, et al. 2017) also found that higher sensitivity fuels had a positive impact on engine thermal efficiency even though RON was more influential.

4.4 Fuel and oil impacts on pre-ignition and mega-knock

The influence of different ethanol fuels was investigated to analyze the effects of wall wetting in a DI engine on pre-ignitions (Mayer, Hofmann and Geringer, et al. 2016b) using the same methodology as outlined in Mayer, 2016a. In this study the fuel volatility was varied in order to change the amount of fuel impinging on the cylinder walls and mixing the oil film from the spray-guided DI fuel spray. They show that the number of pre-ignition events decreases up to 30 v% ethanol due to increasing heat of vaporization and charge cooling, but at 50 v% ethanol the rate of pre-ignition events rises drastically, Figure 11.

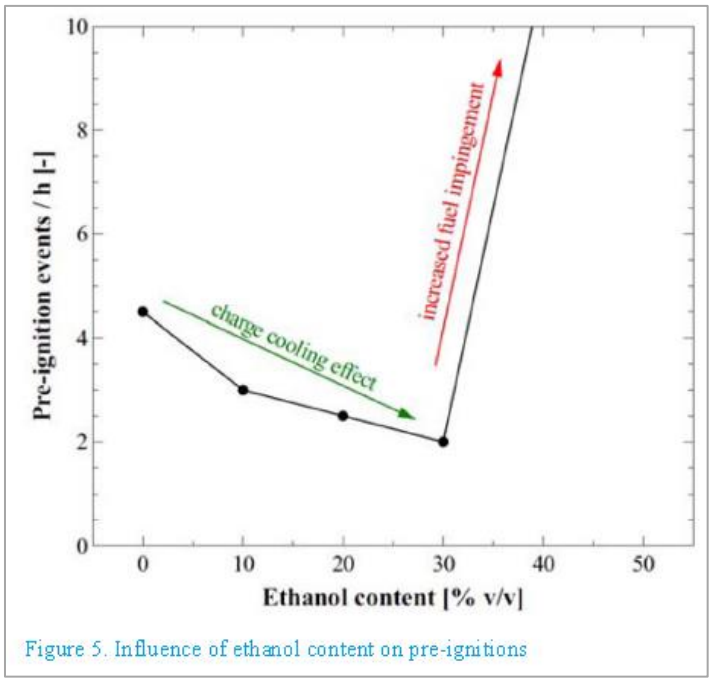


FIGURE 11 EFFECTS OF ETHANOL CONTENT ON RATE OF PRE-IGNITIONS (FROM MAYER, 2016B)

It is hypothesized and then demonstrated that the effect of increased fuel impingement overwhelms the increased charge cooling effect as seen in Figure 12. The "E50specE30" fuel is a blend of the E30 test fuel mixed with neat ethanol to bring it up to 50 v% ethanol, with similar volatility curves as E50. It is also noted that the tendency for mega-knock events is greatly reduced relative to the frequency of pre-ignition events due to increased charge cooling at higher ethanol concentrations.

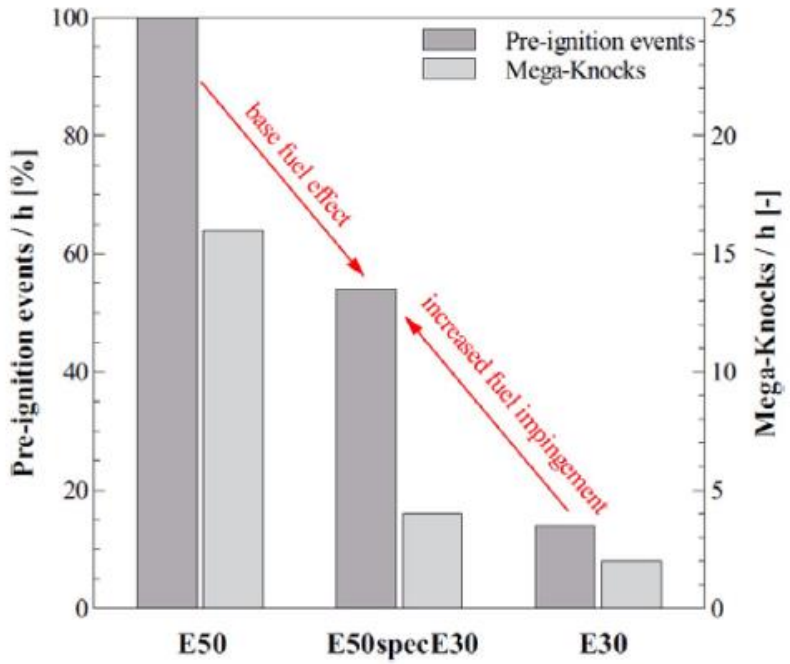


Figure 6. Influence of different base fuels and increased fuel impingement on pre-ignitions

FIGURE 12 BASE FUEL AND FUEL IMPINGEMENT EFFECTS ON PRE-IGNITIONS (FROM MAYER, 2016B)

From these experiments and others, Mayer, 2016b develop a model for the amount of liquid fuel that evaporates from 150°C up to the final boiling point to correlate almost perfectly with the rate of pre-ignition events as shown in Figure 13, reinforcing the hypothesis that droplets formed by fuel-oil mixture can be a significant contributor to pre-ignition.

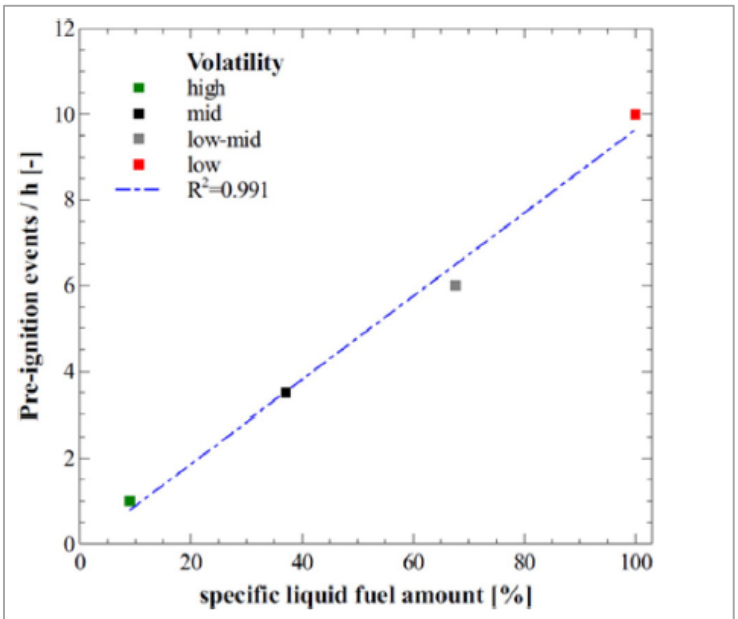


Figure 12. Results of the linear regression for the specific liquid fuel volume on the pre-ignition frequency

FIGURE 13 CORRELATION OF SPECIFIC FUEL VOLUME TO PRE-IGNITIONS (FROM MAYER, 2016B)

4.5 Fuel Effects on Tailpipe and Evaporative Emissions

Because of the rising use of ethanol around the 2007 timeframe, West (West, et al. 2007) acquired a Saab 9-5 flex fuel vehicle (FFV) that was certified to Euro 4 emissions. Taking advantage of ethanol's greater anti-knock properties, Saab specified the turbocharged engine at 180 hp on E85, 20% higher than the gasoline power rating of 150 hp. European emissions regulations required certification on gasoline only, however US regulations required certification on both gasoline and E85, so the vehicle was tested on both fuels. As can be seen in Figure 14 the vehicle showed significantly lower NMHC+NO_x and CO emissions over the US06 test cycle when fueled with E85 than with gasoline. Stein (Stein, Anderson and Wallington, An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions 2013) note a CRC study (Haskew and Liberty 2011) which similarly found a statistically significant trend of decreasing NMHC and NMOG for US06. However there were no significant changes to tailpipe emissions noted on the other test cycles. Stein, 2013 also found lower PM emissions with increasing ethanol content.

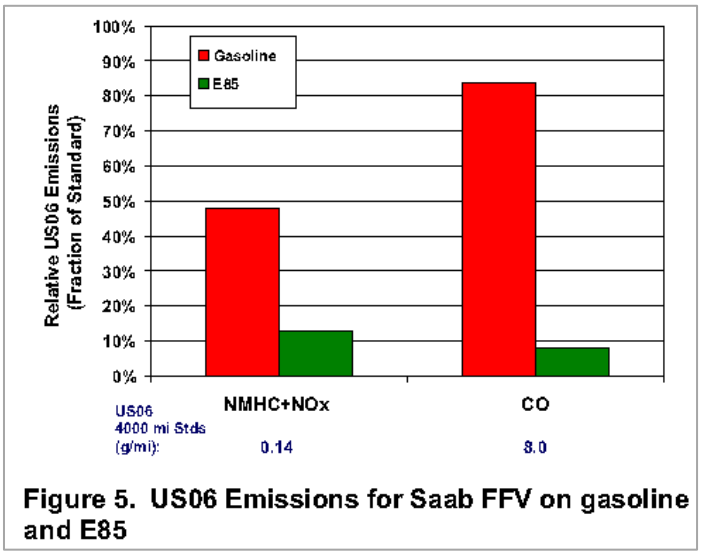


FIGURE 14 EMISSIONS COMPARISON OF AN FFV RUNNING ON GASOLINE AND E85 (FROM WEST)

The EPA regulates the vapor pressure of gasolines in order to limit the evaporative emissions from refueling and other sources on the vehicle. Ethanol-gasoline blends actually have the highest vapor pressure at 10 v% ethanol as shown in Figure 15. The EPA allows a "1 psi waiver" to E10 gasoline blends to encourage the blending of 10% ethanol in gasolines. Stein, 2013 notes that higher levels of ethanol are expected to have little impact on evaporative emissions in modern vehicles.

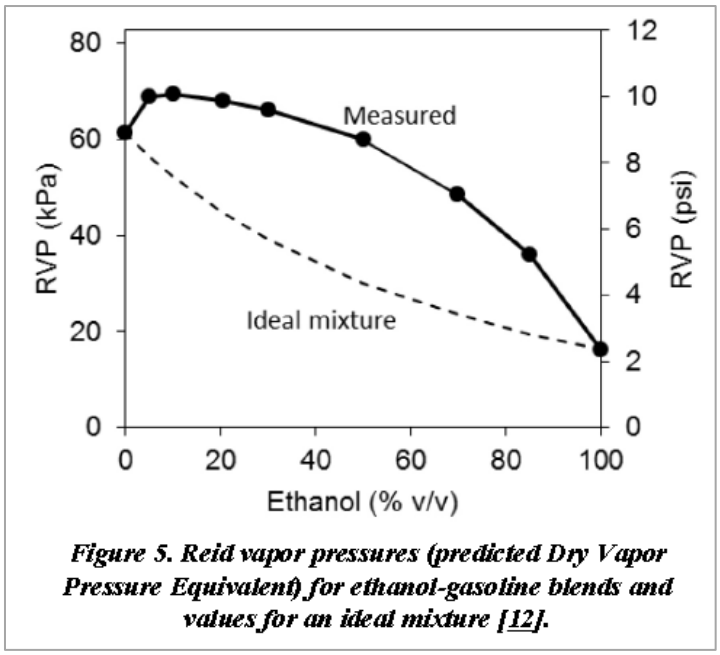


FIGURE 15 REID VAPOR PRESSURE PEAKS AROUND 10% ETHANOL (FROM STEIN, 2013)

5 Solutions to Treating the Engine & Fuel as a System

5.1 Co-Optimization of Fuels & Engines (Co-Optima) Initiative

Transportation accounts for 70% of U.S. petroleum consumption and 27% of the country's greenhouse gas (GHG) emissions, and the internal combustion engines (ICEs) that generate most of these emissions will continue to power vehicles for decades to come. The U.S. Department of Energy's (DOE's) Co-Optima initiative is accelerating the introduction of affordable, scalable, and sustainable fuels and high-efficiency, low-emission engines with a first-of-its-kind effort to simultaneously tackle fuel and engine research and development (R&D) (DOE 2016).

The DOE has developed a 'merit function' in order to quantify the components of efficiency gain that can be expected from high octane fuels as used in high efficiency engines. "The merit function numerically represents the efficiency gain that can be expected compared to a "current market fuel"." (Miles 2016) The contributing factors to efficiency gain are: RON, Octane sensitivity, heat of vaporization, flame speed, distillation and particulate emissions as expressed in the equation of efficiency merit:

$$Merit = \sum \underbrace{\boxed{\frac{(RON_{mix} - 91)}{1.6}}}_{\text{RON}} - \underbrace{\boxed{K\frac{(S_{mix} - 8)}{1.6}}}_{\text{Octane Sensitivity}} + \underbrace{\boxed{\frac{0.01[ON/kJ/kg](HoV_{mix} - 415[kJ/kg])}{1.6} + \frac{(HoV_{mix} - 415[kJ/kg])}{130}}}_{\text{Heat of Vaporization}}$$

$$+ \underbrace{\boxed{\frac{(S_{L\,mix} - 46[cm/s])}{3}}}_{\text{Flame Speed}} - \underbrace{\boxed{LFV_{150}}}_{\text{Distillation}} - \underbrace{\boxed{H(PMI - 2.0)\left[0.67 + 0.5(PMI - 2.0)\right]}}_{\text{Particulate Emissions}}$$

The intent of the merit function is to provide a guide to the DOE research teams to address two important questions: what are the important properties and where should efforts be focused? However, there are stated limitations to what can be achieved by the research being performed under the guidance provided through the merit function however. Specifically, those limitations of the merit function are:

- Applicable only to stoichiometric SI engines
- Considerably simplified (e.g. does not distinguish between NA and turbocharged engines)
- Incomplete knowledge of the impact of many fuel properties (this is a major objective)
- Lack of knowledge of blending effects on properties
- Does not consider properties that do not impact efficiency (e.g. RVP)
- Property interactions have not been investigated thoroughly (e.g. RON & HoV)

- Estimates only an "average" efficiency increase (e.g. does not consider drive cycle effects or different vehicle applications)

Nonetheless, the merit function serves as a useful tool in assigning values to the various contributing factors of efficiency and guiding DOE research efforts. Co-Optima has also incorporated the viewpoints from multi-disciplinary stakeholder groups towards "accelerating the introduction of affordable, scalable, and sustainable fuels and high-efficiency, low-emission engines." Stakeholder groups participating in last year's workshop included trade/consumer groups, petroleum industry, original equipment manufacturers, and the biofuels industry.

5.2 Octane on Demand

Professor John Heywood and co-workers at MIT (Cohn, Bromberg and Heywood 2005) first published the idea of using a high octane fuel such as ethanol only as needed to suppress knock while using a lower octane fuel for the rest of a vehicle's needs in 2005. Their approach involved injecting ethanol directly into the cylinder at high loads for knock suppression and increasing the compression ratio to increase the efficiency of the engine at all operating conditions. The engine would run on gasoline at lower loads where knocking was not present which represents a majority of the time for average driving behaviors. Thus, a small amount of ethanol use was "leveraged" into a much greater savings of gasoline, to the tune of a 30% reduction in overall CO_2 emissions from the gasoline efficiency savings combined with the lower CO_2 from substituting ethanol for gasoline.

The concept of leveraging high-octane ethanol into a greater reduction of gasoline use was applied by Stein (Stein, House and Leone, Optimal Use of E85 in a Turbocharged Direct Injection Engine 2009) to a Ford Motor Company EcoBoost® engine. The engine was modified by adding a PFI system to the DI engine as shown in Figure 16 and by increasing compression ratio to 12:1.

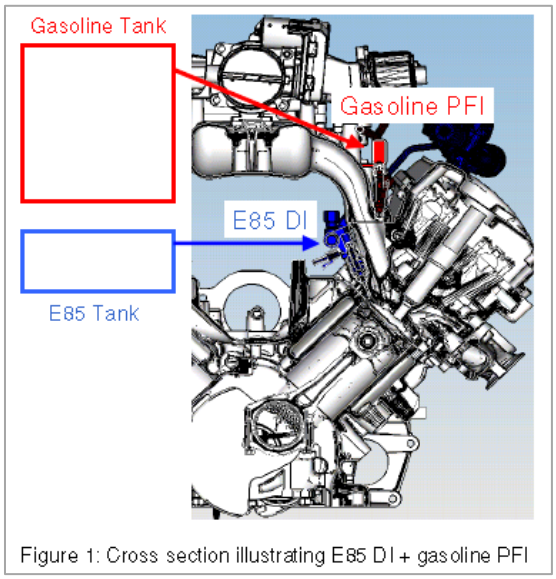


FIGURE 16 ETHANOL LEVERAGING OF GASOLINE ON A FORD ECOBOOST V6 ENGINE (FROM STEIN, 2009)

With the results from testing the engine on a dynamometer they simulated in an F150 pickup truck how much E85 would be required for various drive cycles and overall fuel consumption. The study found that only 1% of the total fuel mass was required from E85 on mild drive cycles like the EPA metro-highway (M-H) test cycle, and 16% on more aggressive US06 driving. However, on the very heavily-loaded scenario of driving up the Davis Dam road in Arizona for 10 miles with a fully loaded vehicle and trailer at it's gross combined weight rating (GCWR) required nearly half the fuel mass to come from E85.

TABLE 2 E85 USE FOR VARIOUS DRIVE CYCLES AND LOADING CONDITIONS (FROM STEIN, 2009)

Table 3: Modeled E85 consumption as a percent of total fuel mass for a 5.0L E85 DI + gasoline PFI engine in a pickup truck

	at ETW	at GCWR
EPA City	1%	19%
EPA Highway	1%	30%
US06	16%	-
Davis Dam	-	48%

This concept is an example of what has been called "octane on demand." While ocatane on demand offers a technically superior solution in terms of CO_2 emissions savings and oil consumption reduction, it has the obvious drawbacks of needing two tanks of fuel on board and requiring vehicle drivers to fill the tanks with two different fuels.

5.3 Higher Octane Floor for US Regular Gasoline

In marked contrast to the octane on demand approach which may be technically superior but has onerous requirements of vehicle operators, there is another approach to improving efficiency and reducing GHG emissions by treating the engine and fuel as a system that is being talked about more openly by automotive OEM executives. That approach makes use of the vehicle efficiency gains stemming from higher octane fuels and moves the onus from the vehicle operator to other stakeholder groups, as seen in part by participation in Co-Optima's workshops:

- petroleum refining
- biofuels industry
- gasoline retailing

In addition to these stakeholder groups needing to undertake changes to their business operations, the United States government would need to regulate (through the EPA), the changes to the gasoline fuels that would be required for use in future vehicles.

Increasing the octane floor of regular grade gasoline sold across the US in order to take advantage of efficiency gains would require the petroleum refining industry to maintain existing octane ratings of their gasoline blendstocks, as noted by Hirshfeld (Hirshfeld, et al. 2014). Leone (Leone, Anderson, et al. 2015) found that higher octane ratings for regular-grade gasoline are an enabler for higher compression ratio, downsizing, turbocharging, downspeeding, and hybridization technologies and that "increasing compression ratios for future SI engines would be the primary response to a significant increase in fuel octane ratings." Furthermore, they state, "higher ethanol content is one available option for increasing the octane ratings of gasoline and would provide additional engine efficiency benefits for part and full load operation," as shown in Figure 17.

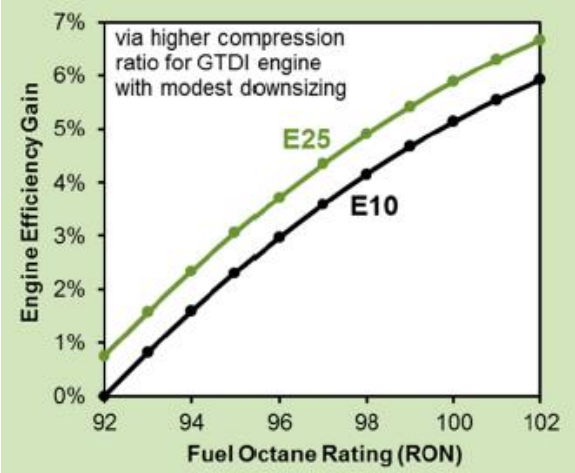


FIGURE 17 ENGINE EFFICIENCY GAINS FROM INCREASING FUEL OCTANE RATING THROUGH ETHANOL CONTENT AND COMPRESSION RATIO INCREASES FOR A GTDI ENGINE WITH MODEST DOWNSIZING (FROM LEONE, 2015)

The biofuels industry would need to take steps to increase the production of ethanol in the US to meet the demand for high octane fuels. Increased production likely would come from both corn starch and cellulosic feedstocks, such as corn stover. Cellulosic biofuels are credited with reducing GHG by at least 60% under the Renewable Fuels Standard (RFS), which would further enhance the lifecycle carbon emissions benefits of a move to ethanol-based high octane fuels. In addition, the gasoline retailing industry would obviously need to ensure the gasoline dispensing equipment is capable of storing and dispensing higher levels of ethanol content in gasoline.

GM and Honda executives said that raising the octane level of pump gasoline in the U.S. is integral to optimizing advanced combustion engines now in development. At the 2016 CAR Management Briefing Seminars Dan Nicholson, VP of Global Propulsion Systems at GM, said, "higher octane fuels are the cheapest CO_2 reduction on a well-to-wheels analysis (SAE International 2016). Fuels and engines must be designed as a total system." Robert Bienenfeld, Assistant VP of Environment and Energy Strategy at American Honda agreed the industry must push for a higher fuel-octane floor in the U.S. prompting positive comments from EPA Director Chris Grundler, noting that the EPA is participating in the U.S. Dept. of Energy's Co-Optima program and has a group working on gasoline octane levels of future fuels.

Chow and coworkers at MIT (Chow, Heywood and Speth 2014) also examined the benefits of a higher octane standard gasoline for the U.S. light-duty vehicle fleet and found "ultimately by redesigning vehicles to take advantage of premium gasoline, fleet fuel consumption and GHG emissions can be reduced by 4.5-6.0% (for 98 RON-100 RON, respectively) over the baseline case, where no additional higher-octane vehicles are introduced."

In a 2017 SAE paper, Darlington (Darlington, et al. 2017) use GHG emissions savings estimates from Leone (Leone, Olin, et al. 2014) for high octane, low carbon fuel (HOLCF) paired with a turbocharged DI engine having it's compression ratio (CR) increased to take advantage of the high octane mid-level ethanol blend fuels.[3] Darlington, 2017 also cite Leone, 2015 and calculate an average benefit level for a 98-RON E25 blend as about 6% for most engines. In terms of vehicle range, Leone, 2014 also found that the 13:1 compression ratio engine gave similar driving range on a 101-RON E30 fuel than the baseline 10:1 engine with regular E10 fuel.

[3] The results of Leone, 2014 indicate that 96-RON E20 fuel enables an increase from 10:1 to 11.9:1 CR and 101-RON E30 fuel enables a further CR increase to 13.0:1 with GHG benefits of roughly 5% and 6%, respectively, on the EPA city/highway cycle; however on the more aggressive US06 cycle the benefit level grows slightly for the 96-RON E20 but more substantially to 9% for the 98-RON E30.

5.4 Greenhouse Gas Emissions of High-Octane, Mid-Level Ethanol Blends

The DOE (Theiss, et al. 2016) has recently published a summary of its efforts investigating the potential of High Octane Fuel (HOF) with 25-40% ethanol blends. DOE investigators came together from Oak Ridge National Laboratory, National Renewable Energy Laboratory, and Argonne National Laboratory with the objective of providing a quantitative picture of the barriers to adoption of HOF and the highly efficient vehicles it enables, and to quantify the potential environmental and economic benefits of the technology. The results of these studies, considered together, show that HOF mid-level ethanol blends could offer significant benefits for the United States. These benefits include a 5-10% efficiency increase in vehicles designed for increased ethanol content and a miles-per-gallon fuel economy parity with E10.

Furthermore, dedicated HOF vehicles exhibit nearly 15% lower well-to-wheels GHG emissions resulting from increased vehicle efficiency and corn ethanol production and use; future corn stover use shows potential to increase the well-to-wheels (WtW) savings to around 30%, Figure 18. By increasing the percentage of ethanol in the fuel supply, the amount of gasoline consumed decreases, thereby further reducing the nation's dependency on crude oil imports and enhancing U.S. energy security.

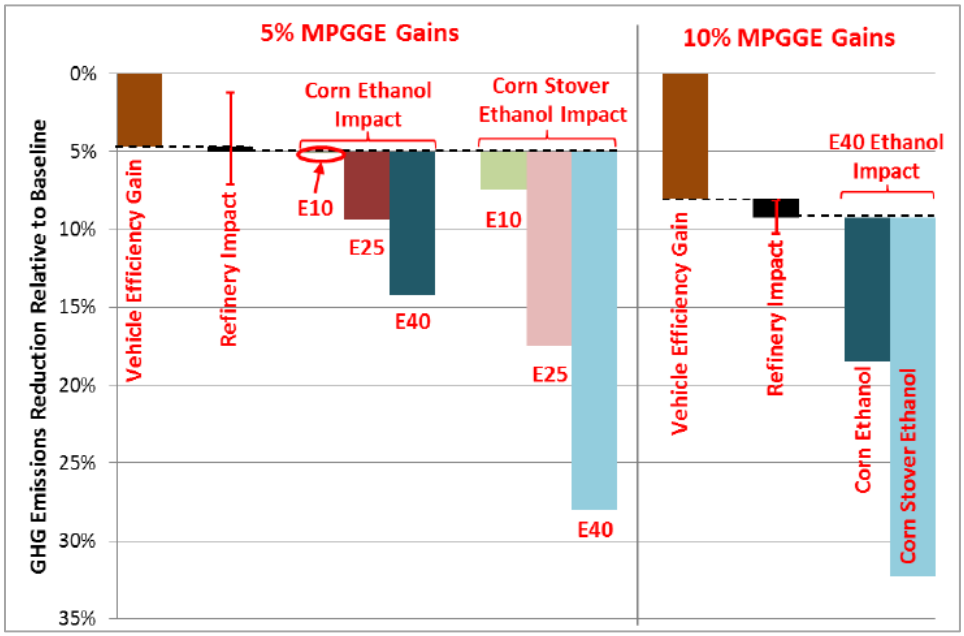


FIGURE 18 WTW GHG EMISSIONS REDUCTIONS IN VEHICLES FUELD BY HOFS WITH DIFFERENT ETHANOL BLENDING LEVELS RELATIVE TO REGULAR GASOLINE (E10) BASELINE VEHICLES (FROM THEISS, 2016)

Kwasniewski et al (Kwasniewski, Blieszner and Nelson 2016) also studied the impact on refinery GHG emissions for 10% and 30% ethanol blends with varying octane ratings. The study found that refinery GHG emissions decline 12% to 27% from a 2017 baseline for the

various 30% ethanol cases due to both the extensive effect of lower crude oil throughput and the generally-overlooked intensive effects of differences in the severity of refining operations.

6 ECONOMICS OF HIGH OCTANE FUELS (HOF)

There have been a number of recent studies related to the economics of increasing the octane levels by raising the ethanol content of gasolines sold in the U.S. and also the cost savings produced by HOLCF use in engines with increased compression ratios.

To estimate the cost of a CR increase that is enabled by HOLCF, Darlington, 2017 cite a National Academy of Sciences study (National Academy of Sciences 2015) and average their cost range to get $100 for improved pistons and rings. The savings in fuel cost resulting from the change to HOLCF was estimated at a net present value of $132, and note that the incremental technology cost approximately balances out the fuel saving credit, using a net zero cost to the consumer. In exercising the EPA's OMEGA model for the impact of HOLCF with high CR engines, Darlington, 2017 found the cost of meeting the model year 2025 GHG emission standards is reduced on a national basis from $23.4B to $16.4B.

Speth and associates at MIT (Speth, et al. 2014) modeled the potential macro-economic effects of transitioning to high-octane (98 RON) gasoline by 2040. They found that if high-octane gasoline in appropriately tuned vehicles accounted for 80% of consumption in 2040, a 3.0–4.4% reduction in total gasoline energy consumption could be achieved. This coincides with a 19–35 metric ton reduction in CO_2 emissions in 2040. The direct national economic benefit of using high-octane fuel is estimated to be $0.4–6.4 billion in 2040, and rises to $1.7–8.8 billion if the social cost of avoided carbon emissions is included.

Hirshfeld, 2014 created a model of the refining economics of US gasoline with particular focus on the octane ratings and ethanol content, Figure 19. The model also examined the impacts of these factors on CO_2 emissions and crude oil use.

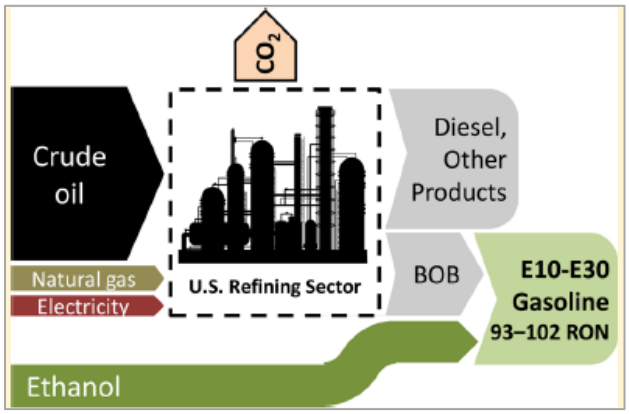


FIGURE 19 MODEL OF US GASOLINE REFINING AND BLENDING WITH ETHANOL (FROM HIRSHFELD, 2014)

Using their linear programming model, Hirshfeld, 2014 examined two ways of increasing the octane of the finished gasoline: by increasing the octane of the petroleum blendstock for oxygenate blending (BOB) and by increasing the volume fraction of ethanol. As shown in Figure 20, increasing the ethanol content of the finished fuel is the lowest-cost means of achieving a higher RON rating. For example, to achieve a 98 RON standard with only 10% ethanol, the additional refining cost is approximately $0.20/gallon. However, a lower cost approach would be to achieve the 98 RON standard by adding 30% ethanol to the gasoline blendstock to make E30 at an additional refining cost of just $0.02/gallon—ten times less costly than the E10 scenario. Due to the efficiency increases enabled by higher octane fuels and the displacement of petroleum by ethanol, the study also found that using E30 to achieve a 98 RON standard would result in the reduction of refinery CO_2 emissions by 3-10% and the reduction of crude oil throughput for gasoline refining by 3-8% compared to the case where E10 is used to meet the 98 RON standard.

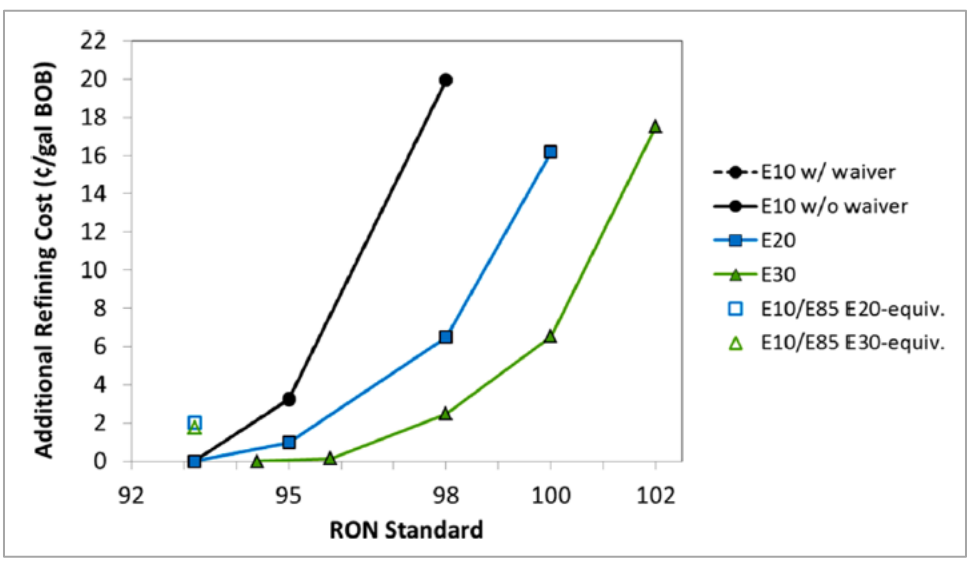


FIGURE 20 ADDITIONAL REFINING COST FOR VARIOUS RON LEVELS AND ETHANOL CONTENTS (FROM HIRSHFELD, 2014)

Relevant to the discussion over the economics of potential future high octane fuels is an analysis by the University of Illinois Department of Agricultural and Consumer Economics (Irwin and Good 2017), which looked at the historical economic value of ethanol in the gasoline blend. The authors state that previous analyses of ethanol's economic value have often adjusted the market value to account for the lower volumetric energy content of ethanol relative to conventional gasoline blendstock for oxygenate blending (CBOB). They suggest that while ethanol generally has had a lower absolute price per gallon on average than CBOB, when adjusted for energy content, ethanol has often been more expensive than CBOB. However, one of the factors that has been neglected has been the value of ethanol as an octane enhancer in gasoline. Ethanol replaces costly aromatic compunds that are used to increase the octane of conventional gasoline made with CBOB. These aromatic octane boosters are sold at a significant price premium, called the "octane premium." An example of these two factors are shown in Figure 21 for the previous 10 year period at the U.S. Gulf.

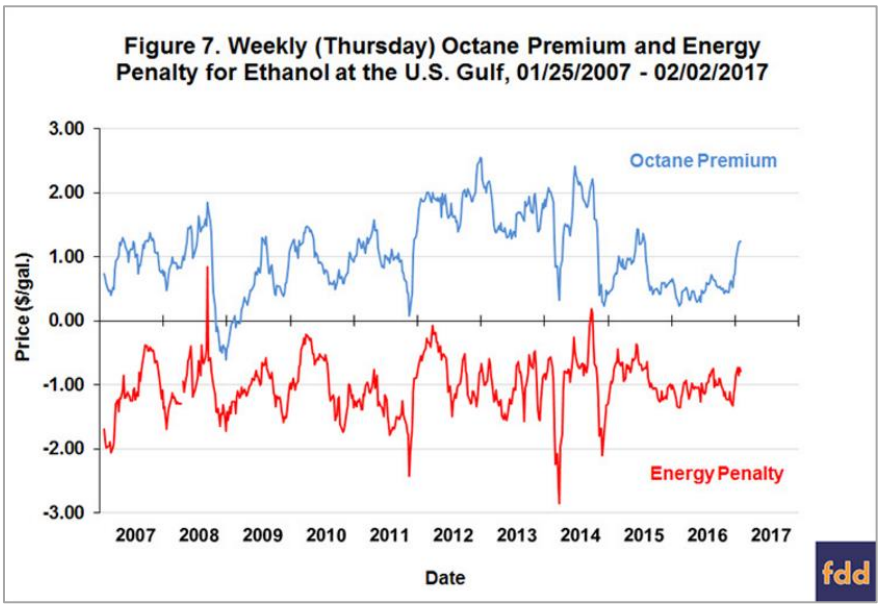


FIGURE 21 WEEKLY OCTANE PREMIUM AND ENERGY PENALTY FOR ETHANOL (FROM IRWIN, 2017)

According to the authors, ethanol's "octane premium" value has typically offset its so-called "energy penalty" over the past decade, as shown in Figure 24.

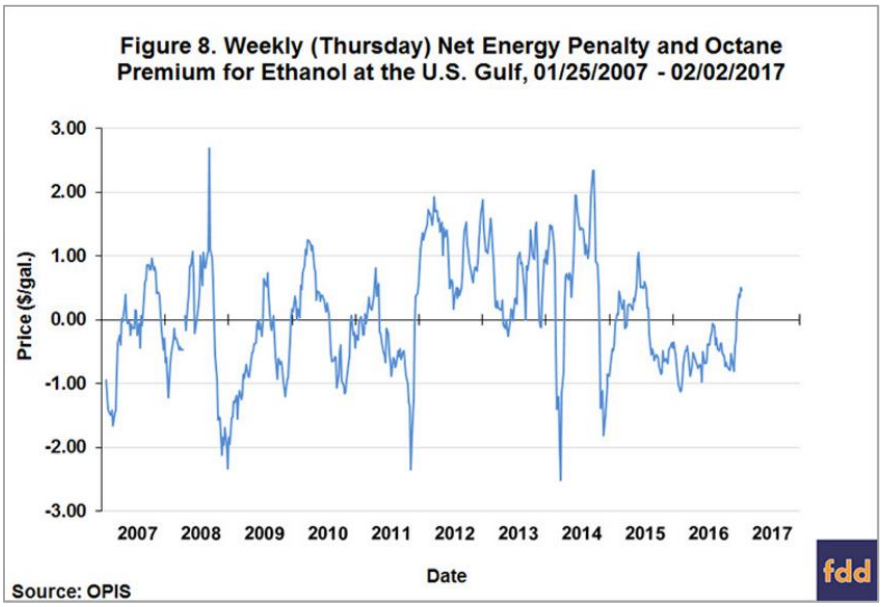


FIGURE 22 NET ENERGY PENALTY AND OCTANE PREMIUM FOR ETHANOL (FROM IRWIN, 2017)

The authors calculated that the fuel ethanol contribution to gasoline provided a net cost reduction of nearly $7 billion dollars between 2008 and 2016. As this analysis is backward-looking, it does not consider the further value ethanol will have in increasing the octane of the gasoline blend to enable high compression ratio engines, without significant refinery capital investment to increase octane production.

Moriarty (Moriarty, Kass and Theiss 2014) have evaluated the implications on the gasoline distribution network of introducing high octane fuels containing 25% or more ethanol, identifying deployment issues that remain to be resolved. Fuel dispensing equipment is certified by the UL (UL LLC 2009) and currently available for E10, E25 and E85 fuels through UL 87A pathways. E25 equipment is very close in price to E10 equipment, in fact one manufacturer has stopped offering E10 equipment for sale, but there is a significant cost premium for E85 dispensing equipment. In order for service stations to dispense an E30 or E40 gasoline, some work remains to be done to assure that the appropriately validated dispensing equipment is available and installed. Moriarty, 2014 concluded that E25 would be the easiest and least costly of the high octane fuels to be deployed, because of the limitations of the existing dispensing equipment. The majority of underground tanks were judged to be capable of storing ethanol blends up to E85, but there are concerns that many stations would need to add another tank to add a higher ethanol blend without eliminating an existing fuel. Lastly, the authors thought the largest barrier to implementation of mid-level ethanol blends is that service stations are not required to keep records of their equipment, so that many station owners are not aware of the capabilities of their equipment.

A market analysis was initiated by the DOE Bioenergy Technologies Office as part of a collaborative research program and summarized by Theiss, 2016 which developed eight deployment scenarios for vehicles adapted for use of High Octane Fuels. These scenarios were modeled by the Automotive Deployment Options Tool (ADOPT). Modeling results showed that E40 was the most likely blend to be accepted by consumers because of the lower costs for consumers and the large greenhouse gas emissions reductions for the automakers. This prediction contradicts the Moriarty, 2014 study which focused only on infrastructure implications and found that E25 is the most easily adopted blend because of existing dispenser certification levels. The model further predicted that more than 60% of light duty liquid fuel could be an E40 blend by 2035. More work will be needed to determine the most economically and technically viable pathway for increasing the ethanol content of high octane fuels.

7 CONCLUSIONS

Modern gasoline engines continue to be developed for ever greater fuel efficiency and performance levels, driven principally by light-duty vehicle standards for greenhouse gas emission and fuel economy. This literature review study found that fuel economy is being improved through the parallel pathways of engine boosting combined with downsizing and increased geometric compression ratio combined with modified inlet valve closing strategies. Both approaches, however, are limited by engine knock. The study also found that another technology that would enable further improvements in engine efficiency is the use of high-octane gasolines blended with ethanol. Gasolines having ethanol in the 15% - 40% range can be blended to increase the anti-knock index (AKI = [RON + MON]/2) thereby enabling engine efficiency improvements.

High octane, mid-level ethanol blends have anti-knock qualities that go beyond it's simple AKI rating, however. Ethanol's high sensitivity (S = RON – MON) and its high heat of vaporization means that engine performance and efficiency can be increased for direct injection (DI) engines more than is indicated by the RON value of the fuel.

The results from the studies reviewed generally support a main conclusion that splash blending ethanol is a highly effective means of raising the octane rating of gasoline and enabling low-cost efficiencies and reduced emissions in modern spark-ignition engines.

8 BIBLIOGRAPHY

autoblog. *Infiniti's new VC-T changes the rules of small turbocharged engines.* Aug 14, 2016. http://www.autoblog.com/2016/08/14/infiniti-vc-t-engine-variable-compression-official/ (accessed May 8, 2017).

Boggs, D.L., H.S. Hilbert, and M.M. Schechter. "The Otto-Atkinson Cycle Engine - Fuel Economy and Emissions Results and Hardware Design." *SAE Technical paper no. 950089.* 1995.

Boretti, A., J. Scalzo, and H. Masudi. "Alternative Crankshaft Mechanisms ad Kinetic Energy Recovery Systems for Improved Fuel Economy of Passenger Cars." SAE Technical Paper 2011-01-0053, 2011.

Chow, E., J. Heywood, and R. Speth. "Benefits of a Higher Octane Standard Gasoline for the U.S. Light-Duty Vehicle Fleet." *SAE Technical Paper 2014-01-1961, doi:10.4271/2014-01-1961.* 2014.

Cohn, D. R., L. Bromberg, and J. B. Heywood. *Direct Injection Ethanol Boosted Gasoline Engines: Biofuel Leveraging For Cost Effective Reduction of Oil Dependence and CO2 Emissions.* Report LFEE 2005-001 RP, MIT Laboratory for Energy and the Environment , 2005.

Darlington, T., G. Herwick, D. Kahlbaum, and D. Drake. "Modeling the Impact of Reducing Vehicle Greenhouse Gas Emissions with High Compression Engines and High Octane Low Carbon Fuels." *SAE Technical Paper 2017-01-0906, doi:10.4271/2017-01-0906.* 2017.

DOE. "Co-Optimization of Fuels & Engines, FY16 Year in Review." 2016. https://energy.gov/eere/bioenergy/co-optimization-fuels-engines (accessed May 12, 2017).

Draper, C.S. *The Physical Effects of Detonation in a Closed Cylindrical Chamber.* Report No. 493, NACA, 1933.

Ferrey, P., Y. Miehe, C. Constensou, and V. Collee. "Potential of a Variable Compression Raio Gasoline SI Engine with Very High Expansion Ratio and Variable Valve Actuation." *SAE Int. J. Engines 7(1):2014, doi:10.4271/2014-01-1201.* 2014.

Haskew, H.M., and T.F. Liberty. *Exhaust and Evaporative Emissions Testing of Flexible-Fuel Vehicles.* Report No. E-80, Coordinating Research Council, Inc., 2011.

Heywood, John B. *Internal Combustion Engine Fundamentals.* McGraw-Hill, Inc., 1988.

Hirshfeld, D., J. Kolb, J. Anderson, W. Studziniski, and J. Frusti. "Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content." *Environ. Sci. Technol.* 48 (2014): 11064-11071.

INFINITI. *INFINITI VC-TURBO ENGINE.* 2017. https://www.infinitiusa.com/now/technology/vc-turbo-engine.

Irwin, S., and D. Good. "On the Value of Ethanol in the Gasoline Blend." *farmdoc daily (7):48.* March 15, 2017. http://farmdocdaily.illinois.edu/2017/03/on-the-value-of-ethanol-in-the-gasoline-blend.html (accessed May 12, 2017).

Kalghatgi, G. *Fuel/Engine Interactions.* Warrendale, PA: SAE International, ISBN 978-0-7680-6458-2, doi:10.4271/R-409, 2013.

Kalghatgi, G., R. Head, J. Chang, Y. Viollet, and et al. "An Alternative Method Based on Toluene/n-Heptane Surrogate Fuels for Rating the Anti-Knock Quality of Practical Gasolines." *SAE Int. J. Fuels Lubr. 7(3):2014, doi:10.4271/2014-01-2609.* 2014.

Kwasniewski, V., J. Blieszner, and R. Nelson. "Petroleum refinery greenhouse gas emission variations related to higher ethanol blends at different gasoline octane rating and pool volume levels." *Biofuels, Bioproducts and Biorefining* 10, no. 1 (2016): 34-46.

Lanzanova, T., M. Nora, and H. Zhao. "Investigation of Early and Late Intake Valve Closure Strategies for Load Control in a Spark Ignition Ethanol Engine." *SAE Int. J. Engines 10(3):2017, doi:10.4271/2017-01-0643.* 2017.

Leone, T., E. Olin, J. Anderson, H. Jung, and et al. "Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO2 for a Turbocharged DI Engine." *SAE Int. J. Fuels Lubr. 7(1):2014, doi:10.4271/2014-01-1228.* 2014.

Leone, T., et al. "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency." *Environ. Sci. Technol.* 49 (2015): 10778–10789.

Mayer, M., P. Hofmann, B. Geringer, J. Williams, and et al. "Influence of Different Fuel Properties and Gasoline - Ethanol Blends on Low-Speed Pre-Ignition in Turbocharged Direct Injection Spark Ignition Engines." *SAE Int. J. Engines 9(2):2016, doi:10.4271.* 2016b.

Mayer, M., P. Hofmann, J. Williams, and D. Tong. "Influence of the Engine Oil on Pre-ignitions at Highly Supercharged Direct-Injection Gasoline Engines." *MTZ*, June 2016a.

Miles, Paul. "The Efficiency “Merit Function” An overview and the path forward ." *presented at Co-Optima Stakeholders Teleconference.* DOE, December 13, 2016.

Mittal, V., J. Heywood, and W. Green. "The Underlying Physics and Chemistry behind Fuel Sensitivity." *SAE Int. J. Fuels Lubr. 3(1): 256-265, doi:10.4271/2010-01-0617.* 2010.

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

Naber, J.D., J.R. Blough, D. Frankowski, and et al. ", “Analysis of Combustion Knock Metrics in Spark-Ignition Engines." *SAE Technical Paper 2006-01-0400.* 2006.

National Academy of Sciences. *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles.* Table S.2, ISBN 978-0-309-37388-3, 2015.

Osborne, R., T. Downes, S. O'Brien, K. Pendlebury, and M. Christie. "A Miller Cycle Engine Without Compromise - The Magma Concept." *SAE Int. J. Engines 10(3):2017, doi:10.4271/2017-01-0642.* 2017.

Prakash, A., C. Wang, A. Janssen, A. Aradi, and et al. "Impact of Fuel Sensitivity (RON-MON) on Engine Efficiency." *SAE Int.J. Fuels Lubr. 10(1):2017, doi:10.4271/2017-01-0799.* 2017.

SAE International. "GM, Honda execs agree: Higher octane gas needed to optimize ICE efficiency." *Automotive Engineering*, Aug 03, 2016: http://articles.sae.org/14940/.

Shelby, M., Leone, T., Byrd, K., Wong, F. "Fuel Economy Potential of Variable Compression ratio for Light Duty Vehicles." SAE Int. J. Engines 10(3):2017, doi:10.4271/2017-01-0639., 2017.

Speth, R.L., E.W. Chow, R.L. Malina, S.R.H. Barrett, J.B. Heywood, and W.H. Green. "Economic and Environmental Benefits of Higher-Octane Gasoline." *Environ. Sci. Technol.* 48 (2014): 6561-6568.

Stein, R., C. House, and T. Leone. "Optimal Use of E85 in a Turbocharged Direct Injection Engine." *SAE technical paper 2009-01-1490.* 2009.

Stein, R., D. Polovina, K. Roth, M. Foster, and et al. "Effect of Heat of Vaporization, Chemical Octane, and Sensitivity on Knock Limit for Ethanol - Gasoline Blends." *SAE Int. J. Fuels Lubr. 5(2):2012, doi:10.4271/2012-01-1277.* 2012.

Stein, R., J. Anderson, and T. Wallington. "An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions." *SAE Int. J. Engines 6(1):2013, doi:10.4271/2013-01-1635.* 2013.

Theiss, T., T. Alleman, A. Brooker, A. Elgowainy, and et al. *Summary of High-Octane, Mid-Level Ethanol Blends Study.* ORNL/TM-2016/42, Oak Ridge National Laboratory, 2016.

UL LLC. *UL announces new certification path for ethanol fuel dispensers.* August 10, 2009. http://www.ul.com/newsroom/pressreleases/ul-announces-new-certification-path-for-ethanol-fuel-dispensers/ (accessed May 2, 2017).

vafamehr, H., A. Cairns, and M. Moslemin Koupaie. "The Competing Chemical and Physical Effects of Transient Fuel Enrichment During Heavy Knock in an Optical SI Engine Using Ethanol Blends." *SAE Technical Paper 2017-01-0665, doi:10.4271/2017-01-066.* 2017.

Vertin, K., B. Schuchmann, W. Studzinski, R. Davis, and et al. "Gasoline Anti-Knock Index Effects on Vehicle Net Power at High Altitude." *SAE Int. J. Fuels Lubr. 10(2):2017, doi:10.4271/2017-01-0801.* 2017.

Weissler, Paul. "2012 Mazda3 Skyactiv achieves 40 mpg without stop / start." *Automotive Engineering*, October 28, 2011.

West, B., A. Lopez, T. Theiss, R. Graves, J. Storey, and S. Lewis. "Fuel Economy and Emissions of the Ethanol-Optimized Saab 9-5 Biopower." *SAE technical paper 2007-01-3994.* 2007.

Williams, J., H. Hamje, D. Rickeard, A. Kolbeck, and et al. "Effect of Octane Number on the Performance of Euro 5 and Euro 6 Gasoline Passenger Cars." *SAE Technical Paper 2017-01-0811, 2017, doi:10.4271/2017-01-0811.* 2017.

Zhou, Z., Y. Yang, M. Brear, J. Lacey, and et al. "A Comparison of Four Methods for Determining the Octane Index and K on a Modern Engine with Upstream, Port or Direct Injection." *SAE Technical Paper 2017-01-0666, doi:10.4271/2017-01-0666.* 2017.