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

FINAL REPORT

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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/

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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

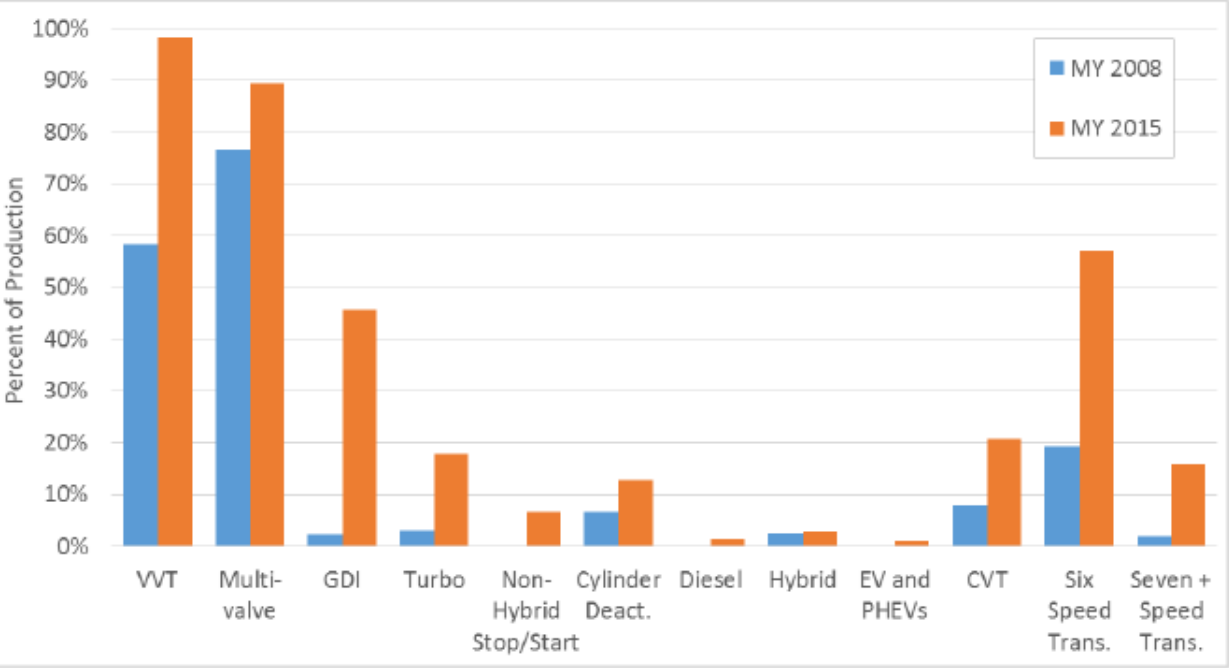

FIGURE 1 LIGHT DUTY VEHICLE TECHNOLOGY PENETRATION SHARE SINCE THE 2012 FINAL RULE (TAR FIGURE 3.10)

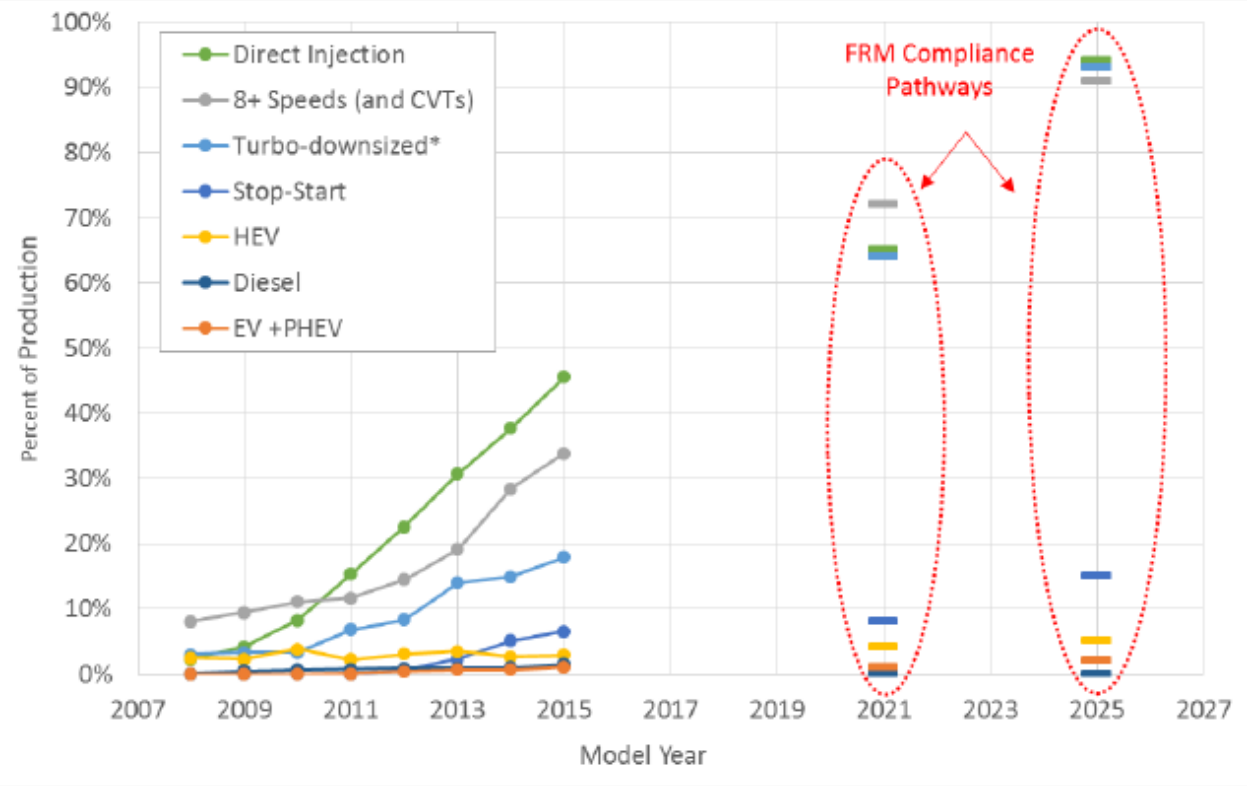

FIGURE 2 TECHNOLOGY CHANGES SINCE MY2009 (TAR FIGURE 3.11)

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.

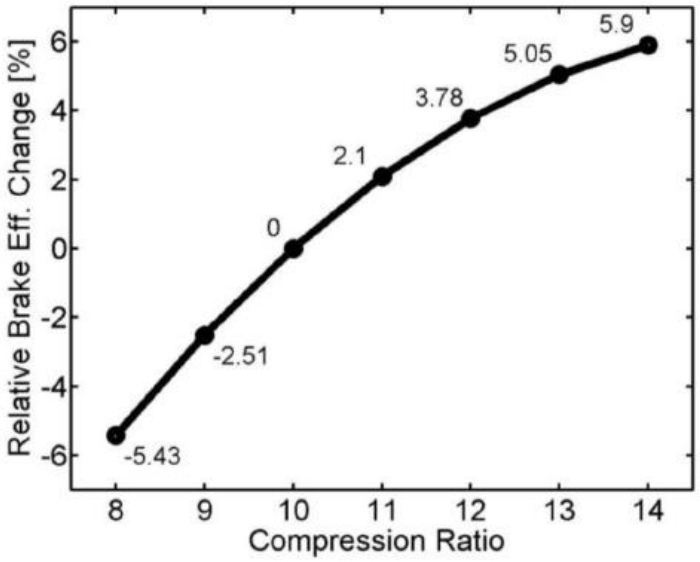

FIGURE 3 AVERAGE RELATIVE BRAKE EFFICIENCY CHANGE VERSUS COMPRESSION RATIO FOR ALL DATA SETS WITH RELATIVE VALUES FROM UNIT CHANGES IN COMPRESSION RATIO LABELLED.[23]

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.

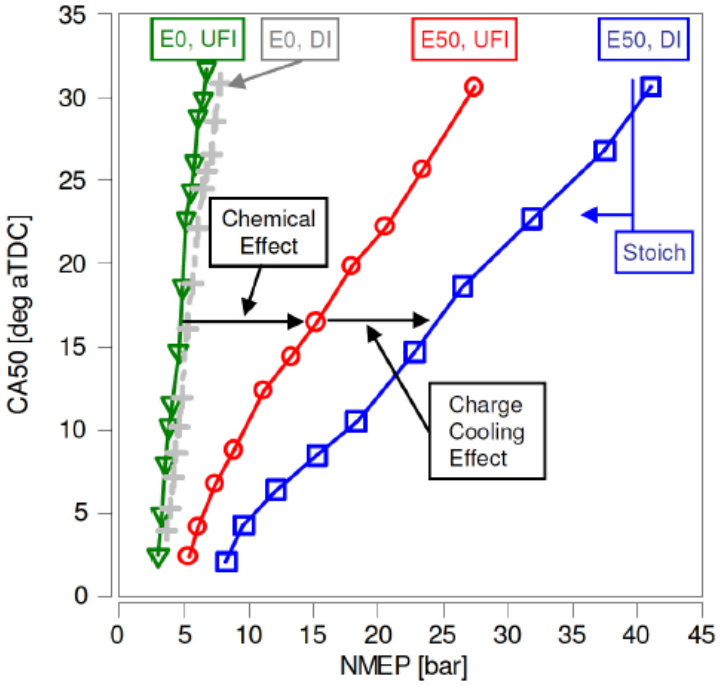

FIGURE 4 SEPARATION OF CHEMICAL OCTANE AND CHAGE COOLING EFFECTS ON KNOCK LIMIT FOR B88E5—R105 AT 10:1 CR AND 1500 RPM.

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.

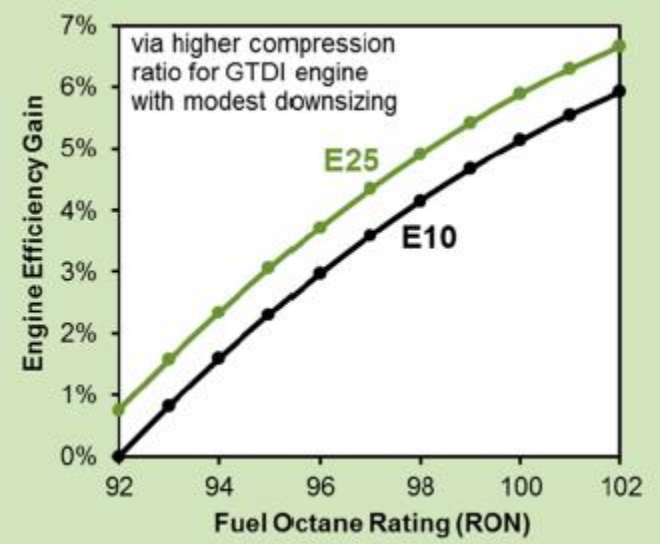

FIGURE 5 ENGINE EFFICIENCY GAINS FROM INCREASING FUEL OCTANE RATING THROUGH ETHANOL CONTENT AND COMPRESSION RATIO INCREASES FOR A GTDI ENGINE WITH MODEST DOWNSIZING.[37]

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

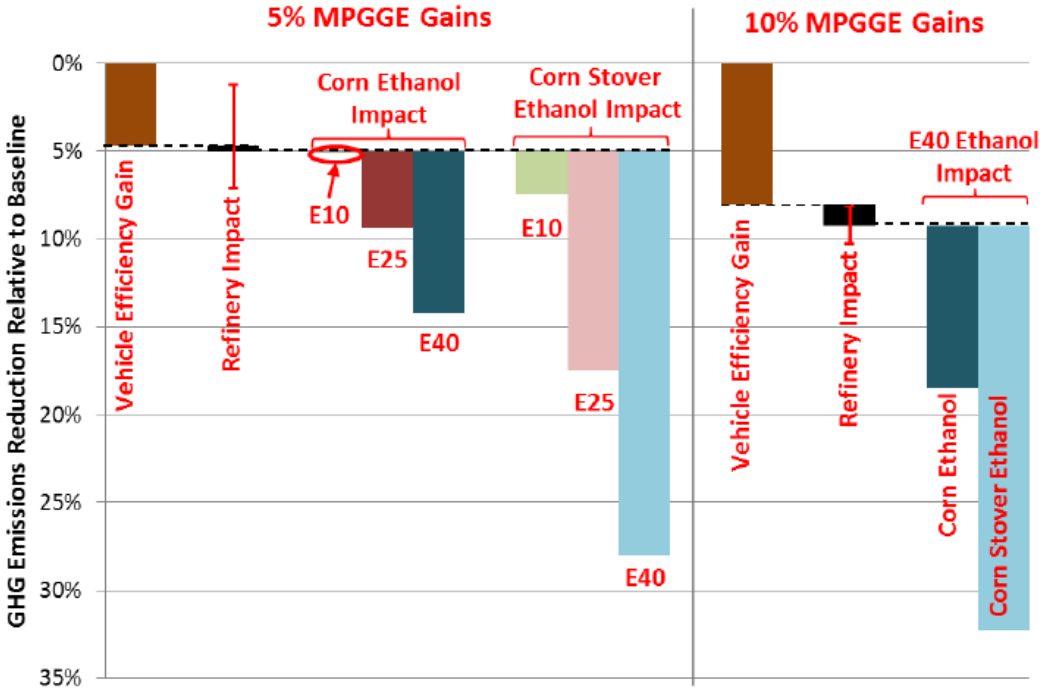

FIGURE 6 WTW GHG EMISSIONS REDUCTIONS IN VEHICLES FUELD BY HOFS WITH DIFFERENT ETHANOL BLENDING LEVELS RELATIVE TO REGULAR GASOLINE (E10) BASELINE VEHICLES.[41]

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.