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High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States

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A B S T R A C T

Ethanol provides a significant contribution to road transportation fuel in the US, Brazil, and elsewhere. Renewable fuels regulations in the US and EU imply that ethanol use will continue to increase in the near future. The high octane rating of ethanol could be used in a mid-level ethanol blend to increase the minimum octane number (Research Octane Number, RON) of regular-grade gasoline. Higher RON would enable greater thermal efficiency in future engines through higher compression ratio (CR) and/or more aggressive turbocharging and downsizing, and in current engines on the road today through more aggressive spark timing under some driving conditions. Such an approach would differ from the current practice of blending ethanol into a gasoline blendstock formulated with lower octane rating such that the net octane rating of the resulting final blend is unchanged from historical levels.

Developing scenarios of future ethanol availability, we estimate that large increases (4–7 points) in the RON of US gasoline are possible by blending in an additional 10–20%v ethanol above the 10% already present. Keeping the blendstock RON at 88 (which provides E10 with ~92.5 RON), we estimate RON would be increased to 94.3 for E15 to as much as 98.6 for E30. Even further RON increases may be achievable assuming changes to the blendstock RON and/or hydrocarbon composition. For example, an increase in blendstock RON from 88 to 92 would increase the RON of E10 from 92.5 to 95.6, and would provide higher RON with additional ethanol content (e.g., RON of 97.1 for E15 to 100.6 for E30). Potential CR increases are estimated for the different estimates of future octane number, including the effect of increased evaporative cooling from ethanol in direct injection engines. For the ethanol and blendstock RON scenarios considered, CR increases were estimated to be on the order of 1–3 CR-units for port fuel injection engines as well as for direct injection engines in which the greater evaporative cooling of ethanol can be fully utilized. Impacts to the fuel refining and blending sector and transition considerations are discussed. While additional work is needed to quantify and optimize the costs and benefits for both the automotive and refining sectors and for consumers, 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.

1. Introduction

In the past, specifications for gasoline properties were re-evaluated when a major change occurred in the oil-automobile industry system. For example, the “oil crisis” in the 1970s and the planned phase-out of tetraethyl lead prompted studies of the optimum octane rating for new unleaded gasoline in the US and Europe [1–4], recognizing that higher octane ratings enable greater efficiency in spark-ignited engines. We are now at another time of great change and opportunity in the transportation industry, including the availability of large volumes of ethanol (with higher octane ratings than petroleum-derived refinery streams [5]), more efficient engine technology options requiring higher octane ratings, and the goals of reducing greenhouse gas (GHG) emissions and petroleum consumption. These significant changes in the fuel/vehicle landscape warrant a re-evaluation of gasoline octane ratings.

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1.1. Ethanol in gasoline

Ethanol now provides a significant contribution to road transportation fuel in the US and Brazil. Most expect that the use of renewable fuels including ethanol will increase in the US, EU, and elsewhere, driven by the multiple potential benefits from the use of ethanol as a transportation fuel: decreased petroleum usage and imports, improved air quality in older vehicles, economic stimulus for agriculture and rural areas, and reduced emissions of GHGs. The magnitude of the GHG impact of ethanol varies depending on the feedstock (corn, sugarcane, lignocellulosic biomass) with the overall net impact being the subject of debate.

Ethanol was added to US gasoline in the 1980s and 1990s at similar concentrations as today (10%v, E10), but total ethanol volumes were considerably less (Fig. 1). In the early 2000s, ethanol use increased due to its use as an alternative oxygenate in reformulated gasoline when methyl *t*-butyl ether (MTBE) was phased out. Reformulated gasoline is required in certain areas to reduce tailpipe emissions of unburned hydrocarbons in older vehicles and to help reduce ground level ozone (smog) formation. Fuel ethanol use has also been spurred by state and federal policies that encourage its use as a renewable alternative to petroleum-derived gasoline and to reduce GHG emissions.

The trend of increasing ethanol use in the US is expected to continue in the next few decades as a result of increasing oil prices and the Energy Independence and Security Act of 2007 which established a new Renewable Fuel Standard (RFS2) that requires up to 36 billion gallons of renewable fuel use through 2022. Much, if not most, of the additional renewable fuel is expected to be ethanol from lignocellulosic biomass, sugar cane (largely imported), and a limited additional amount from corn.

1.2. Ethanol and gasoline properties

Addition of ethanol to gasoline also comes with some challenges, potentially increasing (or decreasing) Reid vapor pressure (RVP) [6], altering distillation properties [7] and preventing transport in pipelines due to risk of water-induced phase separation [8]. The net (or lower) heating value (NHV) of ethanol is also about one-third less than gasoline on a volume basis [9]. While this difference reduces the volumetric fuel economy (miles per gallon or *L*/100 km) observed by consumers and travel range on a tank of fuel, ethanol actually gives a small improvement in the thermal efficiency of engine operation [10,11] (miles per gallon of gasoline-equivalent or MJ/km).

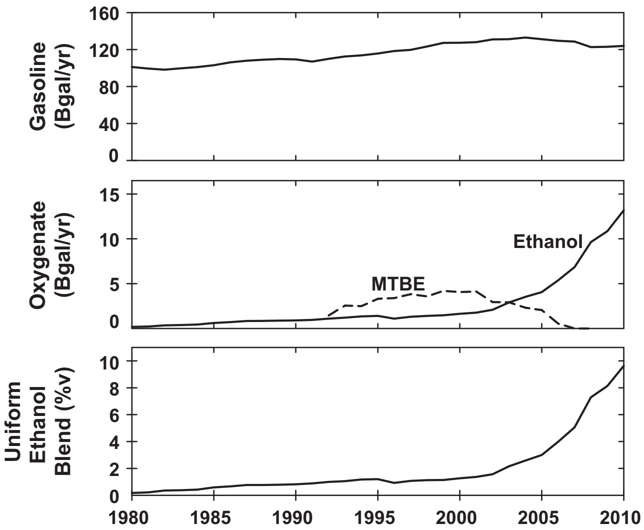

Fig. 1. Historical gasoline, ethanol, and MTBE consumption for US road transportation, and hypothetical nationwide uniform ethanol–gasoline blend level.

The physical properties of ethanol provide important benefits when added to gasoline. Ethanol has both a higher octane rating and a higher heat of vaporization than typical gasoline (Table 1) [9,12,13]. The octane rating of a fuel is a measure of the fuel's ability to resist auto-ignition and knock in a spark-ignited engine. Higher octane-rated fuel is desirable as it enables improved engine efficiency, as discussed in detail below. Two tests are generally used to quantify the anti-knock tendency of fuels: Research Octane Number (RON) and Motor Octane Number (MON). Details of these two American Society for Testing and Materials (ASTM) methods are described elsewhere [14], but both were considered useful when the methods were developed in the 1930s and 1940s. As a compromise, the Anti-Knock Index (AKI, the arithmetic average of RON and MON) has historically been used to describe gasoline octane ratings in the US. Although these test methods are not based on modern engine technology (e.g., fuel supply by carburetor), they persist as industry standards.

The knock-limited performance of gasoline in most modern engines now tends to be better correlated with RON than with AKI or MON [15–17]. Likewise, most automotive manufacturers (including those in the US) now quantify fuel effects on engine performance by RON rather than AKI or MON. Outside the US and Canada, gasoline is differentiated by RON in the marketplace.

To achieve the desired fuel properties in the ethanol–gasoline blends (e.g., E10) sold in retail filling stations, the oil refining industry produces a "blendstock for oxygenate blending" (BOB) to which the appropriate amount of ethanol will be added prior to sale. (For simplicity, the term "blendstock" will be used hereafter to describe this refinery product. "Gasoline" will be used to describe a fully-formulated hydrocarbon fuel containing no ethanol.) Because key volatility properties (e.g., RVP and distillation temperatures) are changed when 10%v ethanol is added to the blendstock, it needs to be formulated to ensure that the final blend properties are within specifications for the appropriate geographical region and season. The need for volatility adjustment was the initial factor leading to the creation of BOBs and remains an important factor for refinery operations.

Ethanol improves octane ratings when added to gasoline. The RON and AKI of pure ethanol are approximately 109 and 99, respectively, much higher than regular or premium-grade US gasoline (Table 1). When ethanol is added to the blendstock, the RON and MON increase of the resulting ethanol–gasoline blend is nonlinear with respect to volumetric ethanol content but has recently been shown to be essentially linear when evaluated using molar ethanol content [14]. The hydrocarbon composition of the blend-

Table 1
Fuel properties of US regular-grade gasoline and ethanol.

	Gasoline[a]	Ethanol
RON	91–93	109[b]
MON	81–84	90[b]
AKI	87–88	99
Density (kg/L)	~0.75 (0.72–0.78[c])	0.79[c]
Stoichiometric air–fuel ratio (kg/kg)	14.6[c]	9.0[c]
NHV (MJ/kg fuel)	44[c]	27[c]
(MJ/L fuel)	33	21
(MJ/kg stoich. mix)	2.8	2.7
HoV (MJ/kg fuel)	0.35[c]	0.92[d]
(MJ/L fuel)	0.26	0.72
(MJ/kg stoich. mix)	0.022	0.092
(MJ/MJ NHV)	0.0080	0.034

[a] Typical US regular-grade gasoline without ethanol.
[b] Ref. [12].
[c] Ref. [9].
[d] Value at 25 °C per Ref. [13].

stock also influences the amount by which ethanol increases the octane ratings of ethanol–gasoline blends [14,18].

The heat of vaporization (HoV) of ethanol is nearly three fold greater than gasoline on a liquid volume and mass basis (Table 1). On a stoichiometric air + fuel mass basis and as a fraction of NHV, the HoV for ethanol is about four fold greater than gasoline. This factor likely contributes to the high RON of ethanol but to an unknown extent.

1.3. Engine efficiency opportunity

The high RON and HoV of ethanol could be leveraged to extract greater efficiency from spark-ignited internal combustion engines. As will be discussed later, if the RON of regular-grade fuels in the marketplace were increased (from ethanol addition and/or changes in hydrocarbon composition), automotive manufacturers could produce new engines with higher compression ratio (CR) and greater operating efficiency. For direct injection (DI) engines, the increase in HoV from greater ethanol content leads to additional evaporative cooling of the air–fuel mixture in the cylinder prior to ignition which inhibits auto-ignition and enables further increases in CR, resulting in even greater overall thermal efficiency. To a lesser extent, the same is true for port fuel injection (PFI) engines, particularly when employing open-valve injection, but much less so for PFI with closed-valve injection. Higher octane-rated fuel also enables higher boost levels on turbocharged and supercharged engines, which may enable engine downsizing for additional fuel economy improvement.

In the interim, until higher-compression and/or downsized and turbocharged engines dominate the on-road vehicle fleet, many of today's engines would also benefit as most are programmed to advance spark timing to a point where the engine functions at the highest efficiency without knock and in doing so minimizes the need for enrichment under these high load conditions. Enrichment reduces efficiency because it uses fuel in excess of the stoichiometric air–fuel ratio to reduce exhaust temperatures and prevent damage to engine components and catalytic converters.

1.4. Gasoline octane ratings and engine technologies

Coordination of increases in engine CRs and gasoline octane ratings would represent a resumption of earlier historical trends. With the exception of the World War II years, the octane ratings of regular-grade gasoline in the US increased steadily from 1930 (60 RON, 60 AKI) until the early 1970s (94 RON, 90 AKI) [19,20]. Since that time, gasoline octane ratings have remained steady or even declined somewhat [21]. Meanwhile, the average CR of gasoline engines in the US increased from approximately 5 in 1930 to 10 in 2008 [16]. Past increases in CR were enabled by a combination of increased octane ratings in gasoline (initially) and advances in engine technology (e.g., knock control through adaptive spark control, variable cam timing, direct injection). Today, new naturally-aspirated (non-turbocharged) gasoline engines in the US typically have CRs in the range of 10–11, with higher CRs for DI engines than for PFI engines, and somewhat lower CRs for turbocharged engines. In Europe, where 95 RON fuel is most common, higher CRs are utilized. Increasing the minimum octane rating of regular-grade gasoline in the US would enable additional future increases in CR and efficiency.

The fuel economy, emissions (tailpipe and evaporative), and safety of LDVs in the US are regulated by the federal government. Critical fuel properties enabling these requirements are understandably subject to similar controls. For example, federal limits on fuel RVP enable evaporative emission limits to be met, and federal limits on sulfur enable exhaust emission limits to be met. However, octane ratings are not regulated at the federal level, despite being the main fuel property limiting the efficiency of spark-ignited engines. Octane rating recommendations for the US are contained in an appendix to ASTM Specification D4814 for gasoline [22]. Some states have established octane rating requirements based on ASTM D4814.

In most of the US, the minimum octane ratings for regular-grade gasoline are 87 AKI and 82 MON (typically corresponding to 91–93 RON) [22]. However, gasoline with less than 87 AKI (e.g., 85 AKI, 89–90 RON) is still accepted in high-altitude regions including the Rocky Mountain states. The minimum octane ratings were relaxed for high-altitude regions because older vehicles (pre-1984) had been shown to have reduced octane rating requirements with altitude; today these vehicles are increasingly fewer in number [22]. In addition, present-day vehicles include adaptive controls with no reduction in octane rating requirement at high altitudes. Since manufacturers design their vehicles to operate without engine damage on any fuel typically sold in the US, the availability of gasoline with low-octane ratings (<87 AKI) has limited the possible CR and efficiency increases for all US gasoline engines on the market.

In the EU, most countries specify that regular-grade gasoline has a minimum RON of 95, which is 2–4 points higher than fuel in most areas of the US, and 5–6 points higher than fuel in US high-altitude regions [23]. This higher RON allows for engines with higher CR and efficiency in the EU as compared to the US, but this RON difference inhibits common global engine designs and calibrations needed for economies of scale.

Despite the recent inclusion of significant quantities of ethanol having high octane value, the octane ratings of regular-grade gasoline in the US are essentially unchanged over the last 40 years. Fuel industry practices have adapted to the increased availability of ethanol, allowing final fuel blends to meet minimum octane ratings by producing and blending with blendstocks having lower octane ratings. In this paper, we consider the merits of an alternative strategy where the minimum octane ratings of regular-grade ethanol–gasoline blends are increased to enable greater overall efficiency in the road transportation sector.

2. Methods

Historical gasoline demand in US road transportation from 1980 to 2010 was determined by subtracting ethanol supply [24] and MTBE supply [25] from total fuel consumption [26]. Historical octane ratings of US fuel from 1983 to 2010 were obtained from the Alliance of Automobile Manufacturers' North American Fuel Surveys. Values reported here are averages of summer- and winter-season averages for fuel identified as regular-grade with minimum 87 AKI. Samples containing 0–2%v ethanol were classified as E0. Samples containing 8–12%v ethanol were classified as E10. Samples containing more than 1%v of other oxygenates (e.g., MTBE) were excluded. In each season of each calendar year, between 120 and 200 fuel samples (obtained from a wide variety of US locations) satisfied the above criteria and were included in the analysis.

Future ethanol and gasoline consumption scenarios were developed from projections in the Annual Energy Outlook 2010 (AEO2010) from the Energy Information Agency (EIA) of the US Department of Energy (DOE) [27], namely the reference scenario, high oil price scenario, and low oil price scenario. Total gasoline and total ethanol usage for road transportation were obtained from the three AEO2010 scenarios. An additional scenario was developed that assumed the maximum potential ethanol volume in the RFS2 mandate (i.e., all renewable fuel is ethanol except that specified as biomass-based diesel) through 2022 with ethanol consumption increasing by 2%/year thereafter. This "RFS2+" scenario assumed the same total energy demand as the AEO2010 reference scenario, but with ethanol substituting for gasoline on an NHV-adjusted basis. For each scenario, hypothetical nationwide-average "uniform ethanol–gasoline blend" concentrations were calculated for each year by dividing the ethanol volume by the combined ethanol and gasoline volume.

Estimates of RON of ethanol–gasoline blends were calculated using the methodology introduced by Anderson et al. [14] in which the RON of an ethanol–gasoline blend ($\mathrm{RON_{blend}}$) is a linear function of the molar ethanol concentration (x_{alc}), the RON of the gasoline blendstock ($\mathrm{RON_{gasoline}}$), and a blending RON value ($b\mathrm{RON_{mol,alc}}$) for ethanol in the blendstock, as shown in the following equation:

$$\mathrm{RON_{blend}} = (1 - x_{\mathrm{alc}})\mathrm{RON_{gasoline}} + (x_{\mathrm{alc}})b\mathrm{RON_{mol,alc}} \tag{1}$$

Molar ethanol concentrations were calculated using Eqs. (2) and (3), where C_{alc} = volumetric concentration (%) of ethanol, and r_{mv} = ratio of liquid molar volumes of ethanol and gasoline blendstock (v_{alc} and v_{gasoline}, cm^3/mol).

$$x_{\mathrm{alc}} = C_{\mathrm{alc}}/[C_{\mathrm{alc}} + (1 - C_{\mathrm{alc}})r_{\mathrm{mv}}] \tag{2}$$

The liquid molar volume ratio, r_{mv}, was estimated using molecular weights (M_{alc} and M_{gasoline}, g/mol) and densities (ρ_{alc} and ρ_{gasoline}, kg/m^3) of the alcohol and blendstock.

$$r_{\mathrm{mv}} = v_{\mathrm{alc}}/v_{\mathrm{gasoline}} = (M_{\mathrm{alc}}/\rho_{\mathrm{alc}})/(M_{\mathrm{gasoline}}/\rho_{\mathrm{gasoline}}) \tag{3}$$

All calculations assume a blendstock with a representative molecular weight of 110 g/mol and density of 0.75 kg/L at 25 °C. Ethanol has a molecular weight of 46 g/mol and density of 0.785 kg/L. For this combination of properties, r_{mv} = 0.40. Eqs. (1)–(3) are summarized in Fig. 2 showing estimated RON values of ethanol–gasoline blends following contour lines of constant blendstock RON.

RON calculations for future ethanol–gasoline blends assume a blendstock having RON of either 92 or 88. The former corresponds to the RON of the predominant gasoline (containing no ethanol) in the year 2000. The latter is the estimated RON of blendstock to make the predominant gasoline (E10) in 2010. The calculations assume a molar-based blending RON value ($b\mathrm{RON_{mol,alc}}$) for ethanol of 108.6 that equals the RON of pure ethanol [12] and was found to be representative of its blending into typical market gasolines and blendstocks [14]. This approach may provide a conservative RON estimate [18].

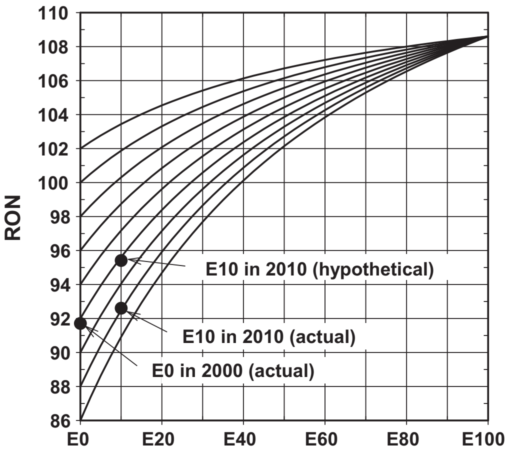

Fig. 2. Estimated RON values for ethanol–gasoline blends with contour lines of constant blendstock RON. Also shown are data points for prevailing regular-grade gasoline in calendar years 2000 and 2010, as well as a hypothetical case for E10 if the RON of E0 found in 2000 had been maintained as the blendstock to create the final E10 blend in 2010.

Additional knock resistance from fuel evaporation ("cooling" octane number) was estimated based on literature data. Evaporative cooling benefits were assumed to be negligible for PFI engines [28]. Okamoto et al. [29] reported a 4 ON benefit for E0 gasoline at wide-open throttle with DI as compared to PFI. Kasseris [30] reported that the cooling octane number increased steadily from 5 ON for E0 gasoline to 18 ON for E85 in a turbocharged DI engine. In the present study, cooling ONs for ethanol–gasoline blends in DI engines were linearly interpolated between these values (ranging from 4.5 ON for E0 to 9.3 ON for E30). This approach agrees reasonably well with a more indirect approach based on a 1 ON benefit per 7 K reduction in intake air temperature [31] using estimated air–fuel mixture temperature reductions for DI with gasoline and ethanol [29,30]. The total ON available for DI engines was assumed to be the sum of RON and the additional cooling ON. This is considered an upper bound as evaporative cooling also contributes (to an unknown extent) to the high RON of ethanol.

Estimates of increased engine efficiency assume an increased CR strategy only, which is conservative since turbocharging and downsizing opportunities are not included. The baseline CRs for PFI and DI engines are assumed to be 10 and 11, respectively. The calculations assume a 1 CR increase is enabled by a 5 ON increase in the fuel [31]. Overall efficiency increases are calculated assuming a typical non-linear CR response [32,33] developed for a reasonable range of cylinder displacements (300–800 cm^3/cylinder).

3. Results and discussion

3.1. Historical gasoline data

As shown in Fig. 1, ethanol has come to satisfy a significant fraction of US fuel demand over the last decade. Ethanol used in LDVs rapidly increased from approximately 1.6 billion gallons (6.1 billion L) in 2000 to approximately 13 billion gallons (49 billion L) in 2010. Most of this ethanol has been incorporated in increasing amounts of E10. Interest is growing in the use of mid-level blends (e.g., E15–E30), manifested for example by the recent issuance of a US. EPA waiver allowing the use of E15 in model-year 2001 and later vehicles [34], though additional administrative and technical hurdles remain before this fuel will be present in the marketplace. The remaining outlet for ethanol in gasoline is high-level ethanol fuel blends previously commercially identified as E85 (containing 70–85%v denatured ethanol). A recent change in the ASTM D5798 specification [35] now allows 51–83%v ethanol in high-level blends. These high-level blends are only for use in flex-fuel vehicles (FFVs) designed for compatibility with E0, E10, E85, and their mixtures. At the end of 2011, over 9 million FFVs were registered in the US and comprised 4% of the LDV fleet. This percentage is steadily increasing due to recent increases in FFV production particularly by the domestic automakers [36]. Due to limited E85 availability and typically uncompetitive pricing on an energy basis, E85 comprised only 1% of total fuel ethanol use in the US in 2009 [26].

To convey the increase in ethanol volumes relative to total fuel demand, the lower panel in Fig. 1 shows the increase of a hypothetical uniform ethanol–gasoline blend (%v), defined here as the overall nationwide average ethanol concentration if all of the ethanol had been uniformly blended into the US gasoline pool. Future projections of this metric can be useful to help anticipate the need for changes in usage and capability requirements for future vehicles and supply infrastructure [36].

The refining industry has adapted their blending practices by creating blendstocks for oxygenate blending (BOBs) for E10 that have considerably lower octane rating than a similar grade of finished gasoline lacking ethanol (E0). The adoption of this approach is seen in Fig. 3, summarizing survey data from US retail filling stations, specifically for measured octane ratings of unleaded regular-grade fuel identified as 87 AKI at the pump. In 1983, the measured octane ratings for regular-grade E10 were 90.4 AKI and 95.4 RON, considerably higher than the minimum 87 AKI and the measured octane ratings for E0 (87.5 AKI and 92.0 RON). Octane ratings above the minimum shown on the pump label are termed octane "give-away" by the oil industry (but could provide a benefit to the consumer). With E10 in 1983, the octane "give-away" occurred because ethanol volumes were small (E10 comprised less than 4% of regular-grade fuel based on Fig. 1 data). At these volumes, refineries would have found it impractical (and not cost-effective) to make small quantities of a lower-octane-rating blendstock for E10; thus the ethanol was likely "splash-blended" into the prevailing regular-grade E0 gasoline. In fact, using the molar estimation approach, the measured octane ratings for regular-grade E10 in 1983 (90.4 AKI and 95.4 RON) were approximately equal to what would be predicted for an E10 (90.0 AKI and a 95.6 RON) made from a blendstock having the octane ratings of the average regular-grade E0 at this time (87.5 AKI and 92.0 RON). This estimate for RON can be obtained in Fig. 2 by following the 92-RON blendstock contour line from E0 up to approximately 95.6 RON for an ethanol content of 10%v (E10).

By 1990, the average octane ratings of regular-grade E10 had decreased considerably and remained essentially unchanged through 2010, with the average AKI and RON difference between E10 and E0 having decreased to approximately 1 ON. This change reflects the adaptation of refining and blending practices to greater ethanol content by production of blendstocks with lower octane ratings. Using the molar estimation approach for octane ratings Eqs. (1)–(3), and based on the measured E10 octane rating in 2010 (92.6 RON), we estimate the average octane rating of the blendstock for making E10 had been reduced to approximately 88 RON. This result can be obtained in Fig. 2 by locating the contour line that crosses 92.6 RON at E10 and following it back to an ethanol concentration of 0% (E0) and reading the appropriate RON value of 88 (i.e., for the blendstock portion of the fuel).

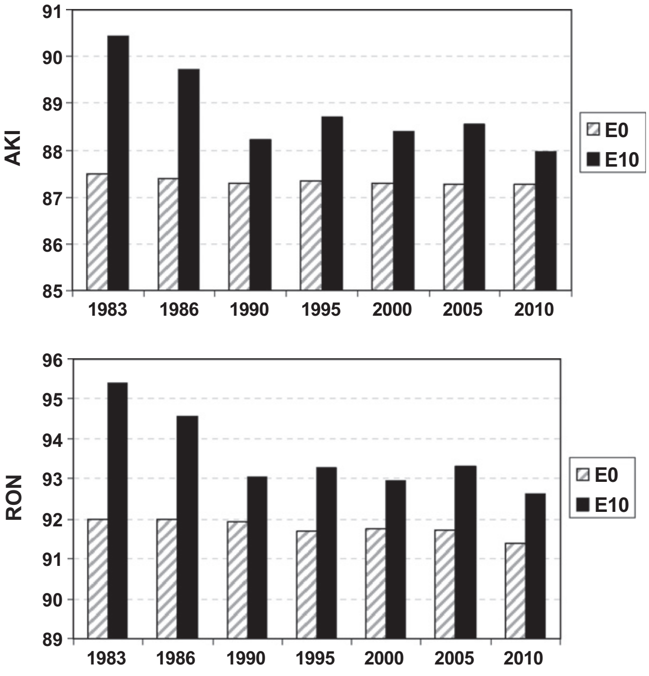

Fig. 3. Average octane ratings (AKI and RON) for regular-grade unleaded gasoline identified as 87 AKI at filling station pumps in nationwide surveys of US retail filling stations. E0 samples contain 0–2%v ethanol, E10 samples contain 8–12%v ethanol, and all contain less than 1%v of other oxygenates. Data from Alliance of Automobile Manufacturers' North American Fuel Survey.

Hypothetically, if the RON of E0 gasoline in 2000 had instead been maintained in the blendstock for E10 in 2010, then the average RON could have increased to greater than 95 RON (Fig. 2). In practice, in addition to avoiding octane give-away, some of the RON reduction in the blendstock resulted from reduced amounts of C4 and C5 alkanes to meet RVP limits, though this task is partially reduced by a federal waiver allowing an additional 1 psi (6.9 kPa) RVP for fuels containing 9–10%v ethanol. These actions are taken because the addition of ethanol at concentrations up to approximately 30%v increases the RVP relative to the blendstock, with greater impact for blendstocks with lower RVP [6,37]. The maximum RVP is typically reached at approximately 10%v ethanol.

3.2. Future gasoline projections

Four future projections of gasoline and ethanol volumes are shown in Fig. 4. The maximum potential ethanol volume mandated by RFS2 (i.e., assuming all renewable fuel is ethanol excluding the small amount required to be biomass-based diesel) through 2022 is shown in the middle panel as scenario "RFS2+". After 2022, this scenario assumes 2% annual growth in ethanol volume. Also shown are three scenarios from US DOE EIA's AEO2010 [27]: the reference scenario (oil price steadily increasing to $133/bbl [2008dollars] by 2035), a high oil price scenario (increasing to $210/bbl by 2035), and a low oil price scenario (stabilizing at $51/bbl through 2035). All three scenarios involve lower ethanol volumes through 2022 than the maximum potential in RFS2, reflecting expected delays in supply of cost-competitive lignocellulosic ethanol, increasing amounts of advanced diesel renewable fuel products, and production of gasoline- and diesel-range hydrocarbons from biomass. As shown in the top panel of Fig. 4, the oil price assumptions also have a modest impact on projected gasoline demand, only in part due to displacement by ethanol.

Hypothetical uniform ethanol–gasoline blend concentrations (Fig. 4, lower panel) can be calculated from the ethanol and gasoline projections, clearly illustrating the impending E10 "blend wall". Absent significant increases in E85 consumption in FFVs and/or E15 in newer model vehicles, this presents issues in terms of new fuel waiver approvals and specifications as well as engine and infrastructure compatibility [36]. The AEO2010 low oil price scenario varies little from current conditions in which E10 is used nearly nationwide. The AEO2010 reference scenario projects an average ethanol content climbing slowly to E14 by 2030 and then rising to E18 by 2035. The AEO2010 high oil price scenario projects ethanol content reaching E17 in 2020, E23 in 2025 and E29 in 2035. The RFS2+ scenario has ethanol content rising steadily to E24 in 2022 and then to E29 in 2035. Overall, this exercise suggests that it is reasonable to consider ethanol–gasoline blend levels somewhere in the range of E10 to E30 in the next 25 years.

In AEO2010, increasing ethanol volumes over the E10 blend wall are assumed to be used as E85 in FFVs, because ethanol was restricted to either low-level blends up to E10 or E85. As can be inferred from Fig. 2, for a fixed ethanol volume the overall octane rating benefit is greater if blended at low concentrations in large amounts of fuel (e.g., nationwide mid-level blend) than if blended at high concentrations in smaller amounts of fuel (i.e., E10 plus limited amounts of E85). Furthermore, the high octane ratings of E85 cannot be fully exploited in FFVs because for these vehicles to be attractive to consumers, they also need to provide competitive performance with the prevailing fuel (E10) having lower octane ratings. For these reasons, the following analysis assumes all ethanol is used as low- to mid-level blends. (Note that even greater efficiency is possible for ethanol if used in a dual-fuel application

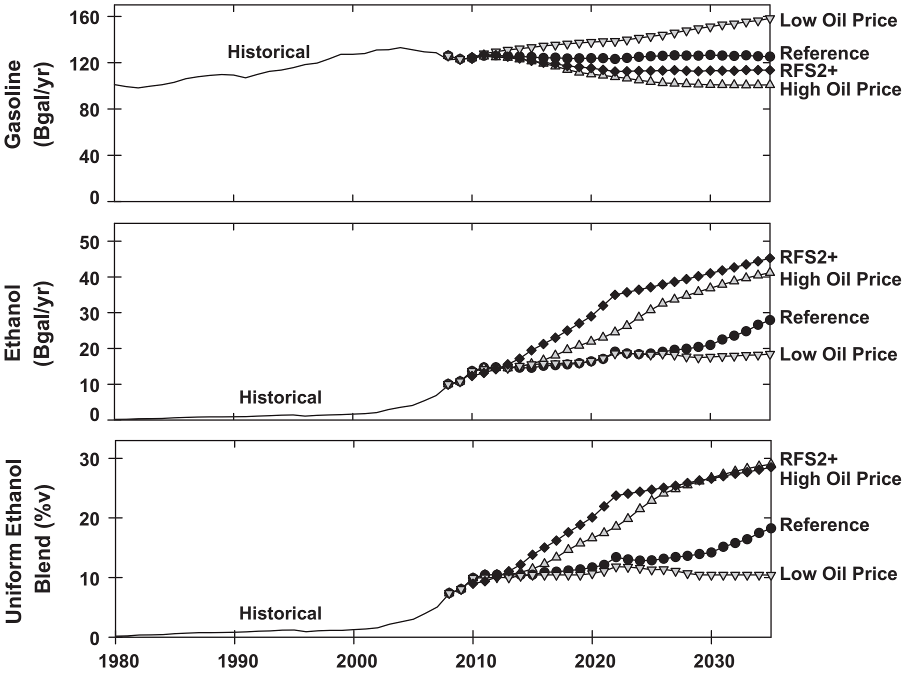

Fig. 4. Historical data and four scenarios of projected gasoline and ethanol consumption for US road transportation, and resulting hypothetical nationwide uniform ethanol–gasoline blend levels. "Reference", "High Oil Price" and "Low Oil Price" are based on similarly named scenarios in AEO2010. "RFS2+" denotes the maximum ethanol scenario under RFS2 plus 2% annual growth in ethanol volume after 2022 using the same total fuel energy demand as the reference scenario.

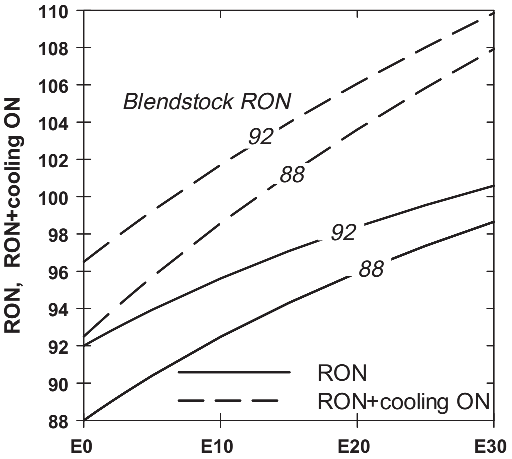

Fig. 5. Estimated RON and RON + cooling ON of ethanol–gasoline blends for two blendstock RON values (88 or 92 RON).

where the ethanol is only used under otherwise knock-limited operating conditions [28,38].)

The RON of future ethanol–gasoline blends can be estimated from an assumed ethanol content and blendstock RON using the molar-based approach [14]. In Fig. 5, the solid lines show estimated RON values for ethanol–gasoline blends for two blendstocks, either 88 or 92 RON, with 88 RON being the estimated RON of the average blendstock used for regular-grade E10, and 92 RON being the average of regular-grade E0 gasoline in the US (and which only recently represented a substantial fraction of US fuel based on the data in Figs. 1 and 3).

If the ethanol content in US fuel does not increase much above E10 in the future, then any octane rating increase would need to come from the blendstock. For example, an increase in blendstock RON from 88 to 92 would increase the RON of E10 from an estimated 92.5 to 95.6. Such a change would produce E10 fuel having a RON similar to that in regular-grade gasoline available in most EU countries.

If ethanol content is increased above E10 in the future, then the additional ethanol could be used to increase the RON of the resulting ethanol–gasoline blend (Fig. 5). If the blendstock is maintained at 88 RON (i.e., no change from 2010), then the RON of these higher ethanol–gasoline blends could be increased to an estimated 94.3 for E15, 95.9 for E20, 97.4 for E25, and 98.6 for E30 (as compared to 92.5 RON for E10). These octane rating increases would be derived solely from increases in ethanol content. If the RON of the future blendstock was also increased through changes in refinery operations, then the RON of final regular-grade ethanol–gasoline blend could be increased further. The RON of blends made from a 92-RON blendstock could see further increases to an estimated 97.1 for E15, 98.4 for E20, 99.5 for E25, and 100.6 for E30 (as compared to 95.6 RON for E10 with the same 92-RON blendstock). As discussed below, any increases in the minimum RON of the fuel supply would enable meaningful corresponding increases in the efficiency of the LDV fleet. While the preceding analysis considered only blendstocks with 88 or 92 RON (selected based on historical refinery and blending practices), additional refinery octane rating increases would enable greater RON (Fig. 2) and greater potential engine efficiency.

Evaporative cooling is an additional factor that deters engine knock in DI engines because the fuel evaporates entirely in the cylinder, with considerably greater cooling from ethanol than gasoline (Table 1). With closed-valve PFI, most of the fuel evaporates in contact with the intake valve and its cooling impact is lost to the engine coolant. Open-valve PFI likely has an intermediate cooling effect. Here, we assume the lower limit (closed-valve) with no cooling benefit for PFI engines. Based on octane number benefits observed in DI engines [29,30], and as discussed in Section 2 of this paper, evaporative cooling in DI engines is assumed to provide an additional 4.5 ON for E0, 6.1 ON for E10, 7.7 ON for E20, and 9.3 ON for E30. As shown in Fig. 5, the total ON (RON plus cooling ON) is approximately 99, 104, and 108 for E10, E20, and E30, respectively, using the 88-RON blendstock currently predominant in the US. Likewise, assuming an increase in blendstock RON to 92, the total ON increases by 2–3 additional ON to 102 for E10, 106 for E20, and 110 for E30.

As has been reported by others, evaporative cooling provides a considerable portion of the anti-knock benefit for ethanol–gasoline blends in DI engines [28–30]. For the 88- and 92-RON blendstocks, the evaporative cooling from the ethanol is estimated to provide about 25–35% of the total ON increase in the blend relative to the blendstock. The percentage increases with ethanol content and blendstock RON because the cooling is assumed to increase linearly with ethanol content whereas the RON increase diminishes with both increasing ethanol content and blendstock RON. Milpied et al. [41] found this percentage to be 30–60% (varying with engine speed) for an E30 blend made using a 92-RON blendstock.

In one sense, these estimates are considered an upper bound as some of the evaporative cooling benefit may already be included in RON. On the other hand, due to the greater temperature sensitivity of ethanol autoignition kinetics as compared to gasoline [39,40], and the fact that modern turbocharged DI engines have lower temperatures at the knock limits than is encountered in the RON and MON tests [40], the total (RON plus cooling) ON estimates shown above may actually be somewhat conservative. For example, Kasseris [30] found that E85 made from a 97-RON blendstock exhibited a total ON of 133 in a turbocharged DI engine. By the approach described here, the total ON for this fuel is estimated at 126, representing an ON increase over the blendstock RON that is 20% less than that reported by Kasseris.

3.3. Future efficiency opportunity from higher octane number ethanol–gasoline blends

The above projections and octane number calculations attempt to quantify a unique opportunity to increase the octane ratings of the future fuel supply, through increasing ethanol content and/or changes in refining and blending practices. An overriding question is whether such changes could result in overall system-wide "well-to-wheel" reductions in petroleum usage and CO_2 emissions at acceptable cost (if any net cost). At present there is insufficient information to answer this question definitively, but discussed below are issues to be considered from both the "tank-to-wheel" (automotive) perspective and "well-to-tank" (oil and refining industry) perspective.

3.3.1. Engine efficiency

Considerable research has been done to quantify the effect of fuel octane ratings on the ability to provide higher efficiency and performance in spark-ignited engines. The actual magnitude of the efficiency gains depends on engine design, operating conditions, and controls. The best quality data is derived from well-defined speed-load combinations using research engines on dynamometers, but the results vary widely due to different engines, test conditions, etc. and additional work is needed to evaluate overall benefits under actual driving conditions. Much of the existing literature data were obtained with older engine designs and were obtained under light loads that are less representative of modern engines and driving patterns. In addition, most studies did not consider ethanol or HoV effects, and many have suspect RON data (either not measured or with questionable accuracy [14]). Despite these caveats, it is clear that higher octane rating fuel presents two main opportunities for higher efficiency: modest gains from spark-advance technology in today's engines and larger gains from higher CR and/or further turbocharging and downsizing in future engines.

For most LDVs on the road today, fuel with higher octane ratings would provide modest improvements in fuel consumption [31]. Nearly all modern spark-ignited engines are equipped with knock sensors and adaptive spark control, allowing the engine to adjust to the octane rating of the fuel under actual operating conditions. Fuel with greater knock resistance allows earlier (more advanced) spark timing at high loads, which improves engine efficiency. Earlier spark timing also reduces exhaust temperature and thus less enrichment is required for component protection at high engine speeds, providing an additional efficiency improvement (modern engine control systems use sophisticated algorithms to minimize enrichment based on inferred exhaust temperature). The observed benefit depends on many factors of engine design, calibration, and operation, but modern engine controls take advantage of both mechanisms. Improvements in fuel efficiency would be realized under high-load or high-acceleration conditions observed in actual consumer driving and present in the US06 drive cycle (which strongly affects the highway fuel economy reported on window stickers). However, fuel with higher octane ratings would not provide a significant fuel economy benefit in the more lightly loaded US EPA Metro-Highway drive cycle used for fuel economy label ratings prior to 2008. Recent changes in labeling procedures now incorporate three additional drive cycles with higher speeds, including US06. The actual reduction in fuel consumption and CO_2 emissions would likely be less than a few percentage points,[1] but it would be realized across nearly all LDVs on US roadways today. Given the scale of fuel consumption by LDVs in the US (140 billion gallons per year at $3–4 per gallon), even a 1% efficiency increase could have an economic impact of several billions of dollars annually.

Future vehicles could achieve higher efficiency through higher compression ratios enabled by fuel with higher octane ratings, an opportunity that is well known [32]. To ensure acceptable operation and durability in all situations, auto manufacturers must design engines with CRs that are compatible with the lowest octane-rated fuel available for the country where that vehicle will be operated. If vehicle manufacturers knew with certainty that the minimum octane rating of fuel would increase at a known future date and remain at these levels, it would be possible to provide future engines that are designed with higher CR and operate with correspondingly higher thermal efficiencies, which could also provide the potential for engine downsizing and turbocharging to further improve vehicle fuel economy [38,41,42]. In addition, certainty about higher ethanol content could allow reliance upon the greater heat of vaporization of ethanol–gasoline blends as an opportunity to further prevent knock and increase CR in those engine designs able to take advantage (e.g., DI).

The CR that is used for an engine is chosen to minimize the occurrence of knock under all operating conditions. In practice, knock typically occurs at high engine loads, i.e., during hard acceleration or while towing. The CR selected during engine development depends on the minimum octane rating of fuel where the vehicle will be used but also depends strongly on engine characteristics (e.g., bore size, burn rate, fuel injection approach, turbocharging), expected operating conditions (e.g., air temperature, engine load and speed), and controlled operating variables (e.g., spark, injection, and valve timing; exhaust gas recirculation).

The CR increase that can be realized in actual engines operating under real-world conditions needs to be determined under both representative and worst-case drive cycles involving many speed-load combinations and transient intermediate conditions.

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[1] US EPA fuel economy certification testing uses ~98 RON (premium-grade) fuel, but EPA regulations only allow auto manufacturers to recommend operation with regular-grade fuel (~91 RON) if there is no more than 3% fuel economy difference between measured fuel economy with the 98 RON and 91 RON fuels.

Literature data [31,43–45] suggest a 1 CR unit increase can be enabled by a 2.5–6 ON increase in the fuel. A value of 5 ON per CR is adopted for subsequent calculations.

The elimination of 85 AKI fuel (typically 89–90 RON) in high altitude regions would be a logical first step towards improving market fuel octane rating in the US since its existence limits the possible CR for all US spark-ignited engines. Elimination of this low octane-rating fuel and requiring a single nationwide minimum octane rating would increase the minimum RON for engine designs from 89 to 91 and could enable an approximately 0.4-CR increase in all future spark-ignited engines. This relatively simple change would affect a very small fraction of fuel produced, but would have an immediate efficiency benefit for vehicles using such fuel (through spark advance and less enrichment) in those areas of the country, and would allow more efficient future use (through higher CR) of nearly all fuel used by the LDV fleet in the US.

Elsewhere in the US, fuel with greater ethanol content with no change in the prevailing 88-RON blendstock (Fig. 5) would enable further CR increases. Relative to the 89-RON E0 baseline, increases of 1.0, 2.0, and 2.9 CR in DI engines are estimated for E10, E20, and E30, respectively, which includes the cooling ON effect, while increases of 0.7, 1.4, and 1.9 CR are estimated in PFI engines without the cooling benefit. Increasing blendstock RON to 92 would enable greater CR increases: 1.6, 2.5, and 3.3 CR (for E10, E20, and E30, respectively) for DI engines and 1.3, 1.9, and 2.3 CR for PFI engines. Because the CR estimates for DI engines are assumed to include cooling from ethanol, automakers would require certainty about the future ethanol content (or more generally the heat of vaporization of future fuel formulations) to design for and fully realize this opportunity.

The efficiency improvement from a change in CR has also been the subject of considerable research, and is likewise dependent on many engine-specific factors. As such, it is not surprising that CR-based efficiency gains reported in the literature vary considerably. One key factor is that the rate of efficiency increase diminishes with increasing CR [9,32,33,44,46,47]. Engine thermal efficiency improvements for the scenarios above are expected to be on the order of 2–5% for the above scenarios (i.e., fuel consumption is reduced by 2–5% after correcting for fuel NHV differences). This result is generally consistent with a recently published German study [48] indicating a 3–5% efficiency improvement opportunity for E20 and E30 blends with a 95-RON blendstock when used in optimized turbocharged DI engines with higher CR.

While the turbocharging and downsizing approach was not included in the present analysis due to a lack of quantitative data on the efficiency benefit under typical drive cycles, this additional option may in fact have greater efficiency potential than the CR approach because such engines are more broadly knock-limited. An updated and more detailed evaluation of the potential efficiency improvement through both approaches is required but is beyond the scope of the present study.

3.3.2. Refinery considerations and efficiency

At a societal level, it would only make sense to increase the RON of regular-grade fuels if there would be an overall, system-wide (refinery plus vehicle) reduction in petroleum usage and/or CO_2 emissions, and if those reductions were cost-effective considering all additional costs for fuel production and/or vehicle technology. Few if any relevant studies were found on this subject. A 1980 study [4] by the European oil industry association CONCAWE evaluated the effect of gasoline with different RON on total well-to-wheel petroleum consumption with an emphasis on the phase-out of lead as an anti-knock additive, and reported that 95 RON with 0.15 g Pb/L gasoline and 92 RON for unleaded gasoline were optimal solutions. However, the study did not consider the impact of ethanol or other oxygenates, was focused on the European fuel market, and is now more than 30 years old. A 2005 study [49] by a research consortium of the Japanese auto and oil industries concluded that an increase in RON from 90 to 95 could provide an overall reduction in well-to-wheel CO_2 emissions and that ethanol addition provided greater reductions than changes in refinery operations. The study, however, considered an ethanol content of only 3%v and was focused on the Japanese vehicle and fuel market.

Finally, stimulated by the 1970s oil crisis and the impending lead phase-out, multiple studies conducted in the US [2,3] were conducted to evaluate optimal octane ratings for the new unleaded gasoline. In their review of this information in 1973, the US Environmental Protection Agency [1] concluded, with several caveats, that “the current rating of 91 RON/83 MON for unleaded gasoline does not appear strictly appropriate on a permanent basis.”

Notably, the current incorporation of 10%v ethanol in gasoline (and even greater projected future ethanol availability) was not envisioned in these studies. As such, none are relevant to the current US fuel market. New studies that consider the current and future US context are needed.

It is expected that the oil industry will continue to adapt their refinery operations to accommodate whatever ethanol content (or other renewable fuel) is required by mandate, regulation, or economics. Gasoline specifications for a variety of properties (e.g., ASTM D4814, federal specifications on sulfur, RVP) need to be met, though they may be modified over time to meet new objectives. The industry can be expected to continue to meet minimum octane ratings by further reducing the octane ratings of blendstocks as the ethanol content is increased unless motivated to do otherwise. Governmental policies may be needed to guarantee higher octane ratings for fuel in the future, achieved by increasing blendstock octane ratings and/or by additional ethanol content. Increasing the octane rating of the blendstock from current levels back to pre-ethanol levels or higher would require changes in refinery operations. Such changes would likely involve a net increase in the cost and possibly the CO_2 burden associated with fuel production; however, little if any publicly-available data could be identified that describes the magnitude of these impacts. Credit for increasing the octane rating of fuel using existing regulatory mechanisms such as state or federal low carbon fuel standards is one possible approach to enable such changes.

3.4. Transition considerations

The transition to a future with a higher minimum octane rating for regular-grade gasoline would require managing various transition issues. If the fuel involved higher ethanol content than E10, protection grade (E0–E10) fuel would be needed for legacy vehicles and non-automotive engines until they were replaced by engines with adequate compatibility. The fueling infrastructure, notably fuel tanks and pumps, also may require upgraded ethanol compatibility. Through coordination and planning, similar transition issues were accommodated during the successful transition from leaded to unleaded fuel.

The availability of a lower ethanol content (and thus higher energy content) fuel in the marketplace could be an obstacle to consumption of the higher ethanol content fuel. The high ethanol content fuel would need to be attractively priced because consumers will consider energy content, as demonstrated by relatively limited E85 consumption in the US to date. In the short term, the Renewable Identification Number (RIN) system associated with RFS2 should incentivize fuel suppliers to competitively price the higher ethanol content fuels (E85 and possibly E15) after the E10 pool is saturated and as the renewable fuel obligation continues to increase. In the long term, continued ethanol mandates, more cost-competitive ethanol production, and/or higher oil prices could also provide competitive ethanol pricing (as has often occurred in

Brazil). A higher minimum floor for octane ratings might be most cost effectively met through higher ethanol content. Finally, the higher octane rating of the future fuel (both RON and cooling ON for DI engines) would provide additional value beyond energy content for optimized vehicles.

Ideally, for maximum societal benefit and to ensure a successful transition, the minimum octane ratings of all US gasoline should be increased, rather than positioning the high ethanol content/high octane number fuel as a premium grade. Automotive manufacturers design around the most widely used fuel grade since high production volumes are required for cost efficiency and competitiveness. If the high ethanol content/high octane number fuel was a premium grade and remained a niche market because of higher price relative to a lower available grade, then automotive manufacturers would most likely not choose to optimize around this fuel.

Finally, FFVs could play an important transition role by providing compatibility with both E85 and future intermediate ethanol-content blends, and could become desirable if higher ethanol blend fuels are attractively priced. While FFVs could be optimized for high ethanol content fuels today, these vehicles would still need to provide competitive performance on the predominant fuel (currently E10) in order for them to be attractive to consumers at the time of purchase. An E85-optimized FFV that is fueled with lower-RON E0 or E10 fuel would show a considerable and unacceptable decrease in power and torque and a moderate increase in fuel consumption.

4. Conclusions

Octane rating is a critical fuel property that plays a primary role in the design, operation, efficiency, and emissions of spark-ignited engines. Although the US federal government regulates LDVs in terms of fuel economy and emissions, the octane rating of the fuel necessary to achieve these objectives is not regulated. The octane ratings of gasoline have not increased since the early 1970s. Higher minimum octane ratings for regular-grade fuel would enable higher compression ratios in future vehicles and is an opportunity to provide greater engine efficiency and meet increasingly stringent fuel economy regulations and expectations. Additionally, the change could benefit all vehicles powered by spark-ignited engines, including PFI and DI engines, hybrid electric vehicles (HEVs), and plug-in hybrid vehicles (PHEVs). Fuel with higher octane ratings will also be increasingly important for advanced engines now being introduced that provide greater efficiency through downsizing and/or turbocharging, and that operate more often at high load where the most efficient operating conditions are limited by knock.

Incorporating ethanol with its inherent high octane rating is one opportunity to enable an increase in the minimum octane rating for regular-grade fuel. This would differ from the current approach in which the octane rating of the blendstock is reduced such that the resulting E10 blend just meets the current minimum specification. Using scenarios of future ethanol availability, we estimate that large increases (4–7 points) in the RON of US fuel are possible by blending in an additional 10–20%v ethanol above the 10%v already present. Greater RON increases may be possible through improvements to the blendstock RON and/or hydrocarbon composition. Potential compression ratio increases were estimated to be on the order of 1–3 CR above respective baselines for PFI engines, as well as for DI engines in which the greater evaporative cooling of ethanol can be fully utilized. Refinery impacts (petroleum consumption, CO_2, cost) from any necessary blendstock formulation modifications (octane rating if needed, and other properties such as RVP) also need to be included for a complete well-to-wheel perspective. Although additional work is needed to quantify the costs and benefits and to determine optimal solutions from the combined system, to the authors it appears that substantial societal benefits could be obtained by capitalizing on the high octane rating of ethanol through the introduction of higher octane number ethanol–gasoline blends to the US marketplace.

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