Quantifying Ethanol CI Benefits in Gasoline Composition

Executive Summary

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The US consumes about 135 billion US gallons per year of gasoline, more gasoline than diesel, accounting for 53% of US total transportation energy use (EIA, 2021a). Light duty vehicles drive about 2,200 billion miles per year (NHTSA, 2021). The primary combustion species of this gasoline is carbon dioxide (CO_2), while remaining carbon in the fuel appears in the exhaust as regulated pollutants. Greenhouse gas (GHG) concerns have risen to the point that both fuel economy and CO_2 are now separately regulated. Traditionally reduction has been achieved through engine and vehicle design improvement and the use of biofuels, primarily ethanol. Currently most US gasoline is sold as a 10% blend of ethanol (by volume) with a 90% blendstock for oxygenate blending (BOB). The BOB is configured to yield a gasoline meeting specification after the ethanol is blended. Both petroleum components and ethanol blend in a way that changes properties in a nonlinear fashion, increasing difficulty in predicting gasoline composition effects.

Although much of the US fleet consists of vehicles with port fuel injection (PFI) and older vehicles still contribute substantially to the emissions inventory, gasoline direct injection (GDI) is now considered to represent the future. However, concern is expressed over the increase in PM associated with GDI. It is unclear whether wisdom gained from fuel effects research on PFI vehicles should be applied quantitatively to GDI vehicles.

When renewable fuels are considered, typically the reduction is assessed for their production and upstream CO_2 impact relative to conventional petroleum fuels. This results in a well to tank (WTT) analysis. However, the fuel change also affects the CO_2 produced by the vehicle, suggesting the tank to wheels (TTW) analysis presented in this report. TTW CO_2 reduction for ethanol blends may be examined from either a fuel-based perspective or a vehicle exhaust inventory perspective. Fuels are typically characterized using a carbon intensity (CI), calculated as a ratio of carbon in the fuel, or carbon dioxide production potential, per unit of mass-based heat of combustion in the fuel. Ethanol has both a reduced carbon content and a reduced lower (or net) heating value (LHV) relative to petroleum species. The CI of ethanol is slightly lower than that of typical petroleum gasoline. CI of Ethanol is around 4% higher than for paraffins in the fuel, but 12% to 18% less than the aromatics in the fuel. The high aromatic CI is associated with a high C:H molecular ratio. Aromatics (mainly from a refinery reformer), ethanol and branched paraffins (mainly from a refinery alkylation unit) serve to raise the octane rating of a gasoline blend.

Gas chromatography has now advanced to the point where gasoline may be characterized by concentrations of its individual constituent species, termed detailed hydrocarbon analysis (DHA). CI may be calculated by employing DHA. ASTM D6729 presents the analytic method. Species may also be gathered into hydrocarbon groups, such as paraffins, isoparaffins, olefins, napthenes and aromatics. DHA species or groups may each be characterized with respect to carbon content and LHV and summed in a weighted fashion to yield CI. Total fuel LHV and carbon content analyses can also yield CI. Generally, variability of fuel analysis has a small effect on conclusions when considering fuels that are intentionally blended or splash blended, but caution is needed in comparing CI of two unrelated fuels, analyzed in different ways, due to measurement variability. C:H ratio was found to be a good correlational estimator of CI for market gasoline blends.

Refinery operations and blending practices are dictated by the best overall value of products sent to the market. These economic considerations, availability of feedstocks and examination of gasoline properties support the conclusion that as ethanol is blended into gasoline, so aromatics are reduced to maintain a constant octane rating. The primary refinery option for lower petroleum octane is through lower severity or throughput for the gasoline reformer, which in turn decreases gasoline aromatic content and carbon intensity. The reduction of aromatics in preparing a BOB for E10 and higher blends results in a net reduction in CI for market fuels. While the actual percentage reduction in CI of 10 percent and higher ethanol blends is not large, the TTW reductions are impressive when applied to national or global fuel consumption. This reduction opportunity applies to nearly all US gasoline consumption of about 140 billion gallons/year. Only 14 billion gallons of ethanol are required to produce the national E10 demand.

CI reductions for ethanol blending were demonstrated for a three component mixture of ethanol, toluene and iso-octane. The findings were confirmed through gasoline modeling covering a variety of scenarios and E10, E15 and E20 blends. Scenarios included maintaining current refinery production and increasing exports to compensate for incremental ethanol, adjusting refinery down to meet domestic demand and keep base E10 case exports constant, and splash blending E15 and E20 using an E10 BOB. CI reduction relative to E0 ranged from 1.41% for E10 to 3.04% for E20 with a dedicated BOB under the scenario of maintaining production with increasing exports, as shown in the figure below.

Figure ES-1: Carbon Intensity for "Set 1" Scenarios (mid-level aromatics) examined in the report

The US gasoline consumed represents about 700 billion pounds of carbon annually, which yields 1.3 billion short (US) tons of CO_2. From the fuel-based CI expected from an informed refinery model, a reversion from very high E10 penetration to a high aromatic E0 gasoline would raise the US CO_2 inventory by 18.3 million tons per year. Conversely, just from fuel CI effects on TTW emissions, a move to E20 would offer a beneficial reduction as high as 33 million tons per year relative to E0 use. Taking into account vehicle efficiency effects embodied in the EPA 1.66% value (NPRM, 2020) for moving from E0 to E10 suggests that E10 currently offers a national TTW reduction of 21.6 million tons of CO_2 annually.

The TTW advantages should be incorporated into WTW comparisons to assure overall accuracy. While the TTW reductions discussed above are more modest than the WTT GHG emissions effects discussed in the literature, the TTW effects are certain. In contrast, the cited WTT emissions component changes vary widely, with US government sources varying in WTW reduction predictions from 21 to 39%, and with far greater variation in the broader literature, due to disparate factors and assumptions such as those related to plant source, agricultural practices, production methods, energy sources and soil effects.

Although this report does not address WTT emissions broadly, the effect of BOB formulation and volume on refinery CO_2 emissions associated with the ethanol blending was explored. Increasing ethanol blend levels results in lower refinery energy and lower CO_2 emissions, but with a more than offsetting increase in CO_2 emissions from hydrogen production requirements. The net is a small increase in refinery CO_2 as more ethanol is used, comprising about 0.5 to 2.5 percent of overall refinery fuel and CO_2 emissions. The change in refinery CO_2 emissions does not have a significant impact on changes in gasoline carbon intensity as ethanol blending is increased.

The modeling demonstrating aromatic reduction resulting from ethanol addition is in strong contrast to the MOVES 3 Fuel Wizard scenario presented by the EPA for a high alkylate E0 (EPA, 2018b). Such a scenario would demand new refinery infrastructure and attractively priced feedstocks that are unlikely to become available.

Aromatic reduction, explained in this report, not only favors CI but also reduces PMI, with implied tailpipe PM 2.5 reduction. Gasoline exhaust PM is considered a major health care concern and has gained greater visibility as a result of GDI adoption and the relative improvement of diesel exhaust PM reduction. PMI is not directly correlated with CI, because the weight and structure of the aromatic components have a complex effect on PMI, but efforts to reduce CI have favorable PMI effects. The figure below demonstrates the disparate contributions of petroleum components to the PMI.

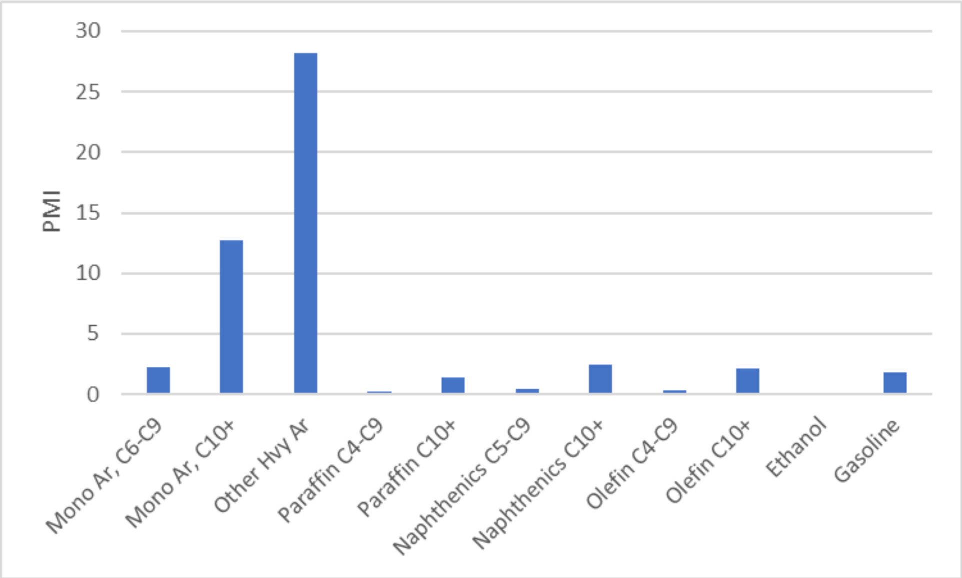

Figure ES-2: PMI of Gasoline, Ethanol and Gasoline Compounds

Measurements of CO_2 from vehicles operated on a dynamometer provide information both on the fuel CI and on the reaction of the engine to properties of the fuel other than LHV. In particular, recent model year GDI engines with high compression ratios will take advantage of a fuel with superior in-use knock resistance to improve efficiency. CO_2 is reduced by the small amount of unburned fuel, other hydrocarbons, particulate matter and non-methane organic gases that are present in the exhaust downstream of the catalyst. The more efficient use of fuel is related to the R-factor, which is employed to assure constancy of data over time as certification fuel specifications are changed. The change from the indolene (used for certification four decades ago) to the present Tier 3 E10 certification fuel is proposed by the EPA to have an R-factor of 0.81, implying that the engine does not show the full penalty of the reduced LHV of the E10. However, there is uncertainty in comparing fuel economy numbers from separate test runs. Data from other programs have shown variation in the reaction of engines to LHV changes, suggesting that the cause for fuel economy change is not one dimensional in LHV.

In summary, ethanol blending into gasoline offers an attractive route for reduction of light duty vehicle TTW GHG emissions while maintaining or raising gasoline octane rating, and while reducing PMI of the fuel.