

An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions

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ABSTRACT

This paper provides an overview of the effects of blending ethanol with gasoline for use in spark ignition engines. The overview is written from the perspective of considering a future ethanol-gasoline blend for use in vehicles that have been designed to accommodate such a fuel. Therefore discussion of the effects of ethanol-gasoline blends on older legacy vehicles is not included.

As background, highlights of future emissions regulations are discussed. The effects on fuel properties of blending ethanol and gasoline are described. The substantial increase in knock resistance and full load performance associated with the addition of ethanol to gasoline is illustrated with example data. Aspects of fuel efficiency enabled by increased ethanol content are reviewed, including downsizing and downspeeding opportunities, increased compression ratio, fundamental effects associated with ethanol combustion, and reduced enrichment requirement at high speed/high load conditions. The effects of ethanol content on emissions are also reviewed, including NMOG/CO/NO_x, particulate matter, toxic compounds, and off-cycle and evaporative emissions.

Considering the engine and vehicle-related factors reviewed in this paper, a mid-level ethanol-gasoline blend (greater than E20 and less than E40) appears to be attractive as a future fuel. To provide high knock resistance, this fuel should be formulated using a blendstock that retains the octane of the current blendstock used for regular-grade E10 gasoline. Further work is needed to recommend a specific ethanol blend level, including analysis of fuel efficiency and CO₂ benefits for representative powertrain/vehicle applications, and of fuel production and supply considerations.

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INTRODUCTION

In recent years there has been intense interest in the use of bio-ethanol as a fuel for internal combustion engines. Drivers for this interest are the desire for energy security and independence, concern for reducing greenhouse gas (GHG) emissions, and economic value to domestic agriculture and related industries. In recognition of the potential benefits of renewable fuel, the U.S. Congress passed the Energy Independence and Security Act of 2007 [1], which mandates the use of 36 billion gallons of ethanol-equivalent renewable fuel by 2022.

The intense interest in ethanol has resulted in a vast amount of information in the technical literature. The purpose of this paper is to provide an overview of the effects of ethanol-gasoline blends on full load performance, fuel

efficiency, and emissions of modern spark ignition internal combustion engines.

The effects of ethanol content on engine component durability and on material compatibility requirements are beyond the scope of this review. However, these aspects have been addressed in flexible fuel vehicles (FFVs) operating on E85 and thus solutions for intermediate blends are expected to be practicable.

FUTURE REGULATIONS

A brief overview of highlights of future U.S. GHG, criteria, and toxic emissions regulations is provided in this section to provide background for the potential impact of ethanol-gasoline blends in meeting these requirements. Regulations in the U.S. are complicated by the fact that the California Air Resources Board (CARB) and the U.S.

Environmental Protection Agency (EPA) have separate requirements. Historically, CARB levels have been more stringent than those of the EPA, and to date fourteen “Green States” have adopted the California requirements for light duty and medium duty vehicles.

In January 2012, CARB adopted new emission rules for cars and light trucks through the 2025 model year (MY), including Low Emission Vehicle III (LEV III) requirements. LEV III includes standards for greenhouse gases, gaseous tailpipe air pollutants, particulate matter (PM), and evaporative emissions. The CARB LEV III standards are more stringent than the current EPA Tier 2 standards; therefore the following sections are a discussion of CARB LEV III rules.

Greenhouse Gases

The GHG standards are expressed as grams of carbon dioxide equivalent per mile ($\text{gCO}_2\text{e/mi}$). The amount of each greenhouse gas emitted is multiplied by a factor that accounts for its global warming potential relative to that of CO_2 over a 100-year time horizon: 1 for CO_2 , 25 for methane (CH_4) and 298 for nitrous oxide (N_2O).

Current CARB and EPA regulations covering vehicles through the 2016 MY are intended to provide a 30% reduction in GHG emissions compared to 2010 levels. LEV III includes regulations applicable for the 2017 MY to 2025 MY, with average reductions of 4.5% per year. The GHG standards are indexed based on vehicle footprint (wheelbase x average track width), and the target $\text{gCO}_2\text{e/mi}$ curves are different for passenger cars and light trucks. Compliance is determined for a manufacturer by comparing the sales-weighted target with the sales-weighted performance for all of the models manufactured in a given year. By 2025, GHG emissions are intended to be reduced by 34% compared to 2016 levels.

Air Pollutants

Vehicle emissions that are regulated due to their adverse impact on air quality are non-methane organic gases (NMOG), carbon monoxide (CO), oxides of nitrogen (NO_x), and PM. For LEV III, fleet average standards for the first three pollutants are reduced to super ultra-low emission vehicle (SULEV) levels by 2025, which represents a reduction of approximately 75% compared to 2014 MY and greater than 99% compared to 1975. The regulation creates new emission bins (intermediate emission level categories) between current SULEV levels and the Zero Emission Vehicle (ZEV) levels. Separate NMOG and NO_x fleet standards are replaced with a combined NMOG + NO_x standard, as shown in [Figure 1](#).

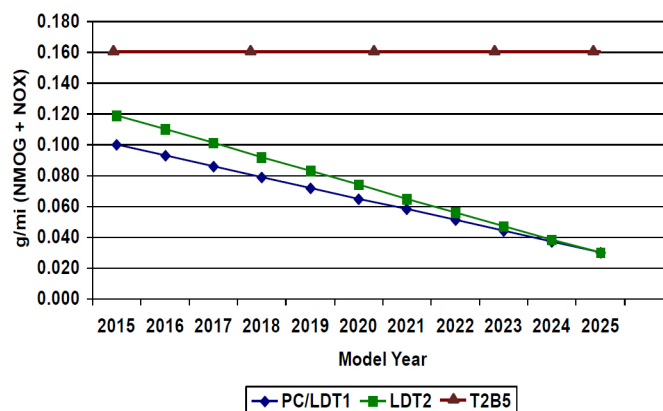


Figure 1. Combined NMOG + NO_x standards of LEV III for passenger car/light duty 1 and light duty 2 category vehicles; EPA Tier 2 Bin 5 shown for reference.

LEV III standards for particulate mass are tightened from the current 10 mg/mile to 3 mg/mile, with a gradual phase-in from 2017 to 2021. The particulate mass standard will be further reduced to 1 mg/mile beginning with 2025 and phasing in through 2028.

Toxic Emissions

A provision of LEV III applies to substitute fuels and new clean fuels in 2015 and subsequent years. This provision requires that the tailpipe emissions of four specific toxic compounds (1,3-butadiene, benzene, formaldehyde, and acetaldehyde) are measured along with CO, NO_x , and the ozone forming potential of the NMOG emissions. CARB requires that the potency-weighted sum of these four toxics be below a limit that is based on the corresponding value for the certification fuel [2].

PROPERTIES OF ETHANOL-GASOLINE BLENDS

Prior to discussing the effects of ethanol-gasoline blends in SI engines, it is instructive to review the fuel property effects of blending ethanol with gasoline. Properties of typical E0 regular grade U.S. gasoline and ethanol are shown in [Table 1](#). Some of the properties blend in a linear manner; for example, the heat of vaporization (HoV) is the mass-weighted average of the values for ethanol and the gasoline blendstock (minus the heat of mixing which is comparatively small [5]). The Research Octane Number (RON) [6] and Motor Octane Number (MON) [7] values blend approximately as the molar concentration weighted average [8]. However, volatility parameters such as vapor pressure and distillation curves exhibit non-linear behavior with ethanol content [9, 10, 11, 12, 13, 14, 15, 16]. Each of these properties is discussed in detail in the sections below.

Table 1. - Properties of typical regular grade E0 U.S. gasoline and pure ethanol [3,4].

	Gasoline	Ethanol
RON	91-92	109
MON	82-84	90
Sensitivity	7-9	19
AKI	87-88	99
NHV ^a (MJ/kg fuel)	42-44	26.9
(MJ/L fuel)	31-32	21.1
(MJ/kg air at stoich)	2.9-3.0	3.0
HoV ^b (kJ/kg fuel)	~350	920
(kJ/kg stoich mixture)	~22	92
Stoichiometric A/F	14.5-14.9	9.0
Density ^b (kg/L)	0.72-0.76	0.785
Molecular Weight (g/mole)	95-115	46

^a ASTM D240 or D4809

^b at 25 °C

Energy Content

It is well known that the energy content of ethanol as measured by the net heating value (NHV) is approximately 33% less than that of gasoline on a volumetric basis (Table 1). NHV is equivalent to lower heating value and net heat of combustion. The NHV per volume of an ethanol-gasoline blend is the volume-weighted average of the values for ethanol and the gasoline blendstock (Figure 2). Hence as the ethanol content of the fuel is increased, the fuel economy in miles per gallon (mpg) and driving range for a given fuel tank size are reduced. This penalty can be partially offset by improved thermal efficiency, as discussed later in this paper.

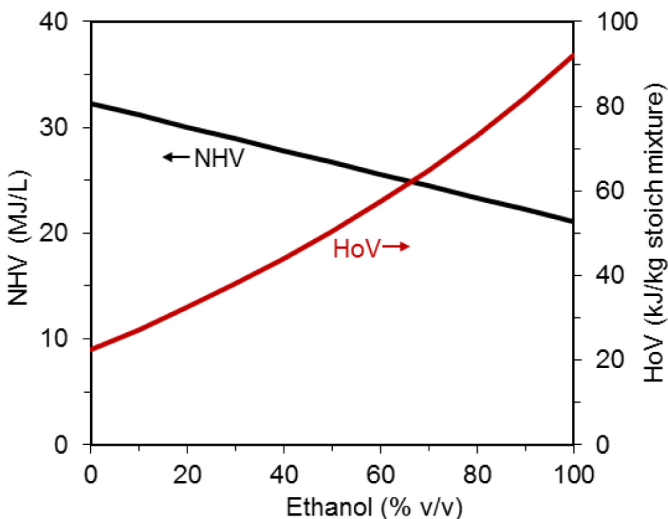


Figure 2. NHV and estimated HoV of ethanol-gasoline blends for a typical gasoline blendstock.

The heat released per engine cycle and thus the full load torque of an engine is directly proportional to the mass of trapped fresh air per engine cycle and to the heating value of the fuel per unit mass of fresh air. As shown in Table 1, typical gasoline and pure ethanol have nearly equal NHV per unit mass of air at stoichiometry, and therefore engine torque per unit mass of air would be equivalent at equal thermal efficiency.

Heat of Vaporization

The heat (or enthalpy) of vaporization represents the amount of energy required to evaporate a liquid fuel. In a direct injection (DI) engine, the amount of cooling of the fresh charge and consequent knock relief provided by evaporation of the fuel is proportional to the fuel flow per unit mass of air. The stoichiometric air-fuel ratio (A/F) of ethanol is 9.0 and that of gasoline is about 14.6 (the exact value depends on the composition of the gasoline), and hence more mass of ethanol than gasoline is required at stoichiometry for a given mass of air. The HoV of ethanol is about 2.6 times that of gasoline per unit mass of fuel, and about 4.2 times that of gasoline per unit mass of a stoichiometric mixture (Table 1). In Figure 2, the HoV per unit mass of stoichiometric mixture for ethanol-gasoline blends for a typical gasoline blendstock is plotted vs. percent ethanol volume.

Octane Number

The RON and MON of an ethanol-gasoline blend can be conservatively estimated by a molar concentration-weighted average of the respective values for ethanol and the gasoline blendstock [8,17]. This behavior results because the molecular fraction and partial pressure of each compound in the fully vaporized fuel during combustion is equal to its molar fraction in the liquid fuel. Because the molecular weight of ethanol (46 g/mole) is much less than that of typical gasoline hydrocarbons (95 - 115 g/mole), the mole fraction of ethanol in a blend is higher than its liquid volume fraction, as shown in Figure 3. The relative difference is particularly evident in low- and mid-level ethanol-gasoline blends. Note in Figure 3 that 10% and 30% ethanol blends by volume correspond to approximately 20% and 50%, respectively, in molar concentration.

The molar-weighted estimate of RON and MON values for ethanol-gasoline blends can be improved by the addition of a non-linear term [17]. In the study of [17], measured RON values were up to 3 RON greater than values estimated by linear molar weighting. The additional term enabled a greatly improved model fit as seen in Figure 4 and can be interpreted as accounting for positive interactions between ethanol and certain hydrocarbons.

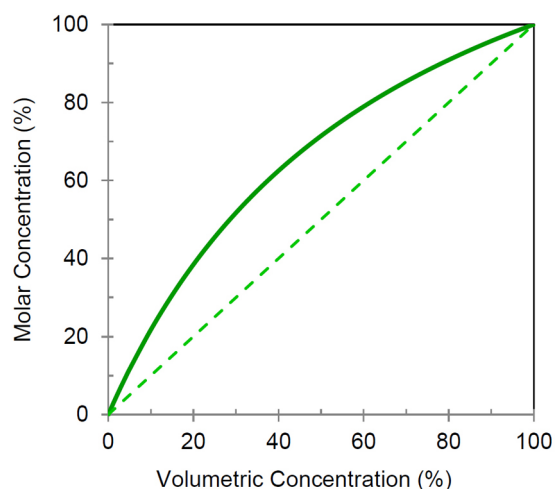


Figure 3. Molar vs. volumetric concentration for ethanol-gasoline blends (solid) and 1:1 reference line (dashed) [8].

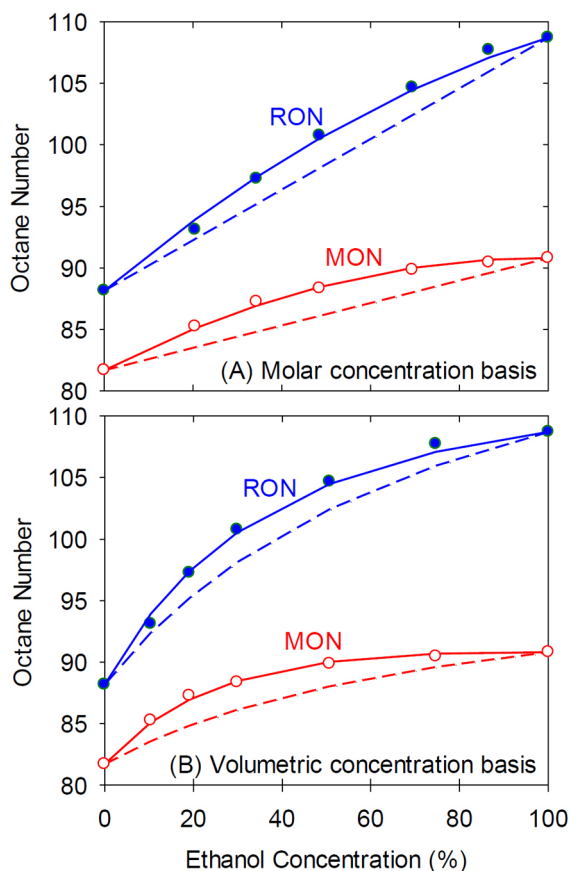


Figure 4. RON and MON values for an ethanol-gasoline blend series versus molar (A) and volumetric (B) ethanol concentration; symbols are measured data, dashed lines show linear molar blending model, solid lines show non-linear molar blending model [17].

The autoignition kinetics of a fuel are dependent on the temperature of the unburned end gas. A measure of this dependency which has been commonly used is the difference between the RON and MON values, defined as the sensitivity (S) of the fuel: $S = \text{RON} - \text{MON}$. As will be discussed in a later section, the sensitivity of a fuel has a profound effect on its knock behavior as test conditions are varied. Because RON and MON values of an ethanol-gasoline blend can be estimated by molar weighting, it follows that the sensitivity can also be estimated by molar weighting.

Vapor Pressure

The most commonly used measure of vapor pressure is the Reid vapor pressure (RVP), defined as the vapor pressure measured at 37.8°C (100°F) in a chamber with a vapor-to-liquid volume ratio of 4:1. RVPs for blends of ethanol in a certification gasoline blendstock are shown in Figure 5 [12]. (EEE gasoline from Haltermann Solutions was used for this study. This is equivalent to fuel with the trade name “Indolene”. Both of these fuels are used for vehicle certification and serve as a standard reference gasoline without additives and having consistent, well-defined properties.)

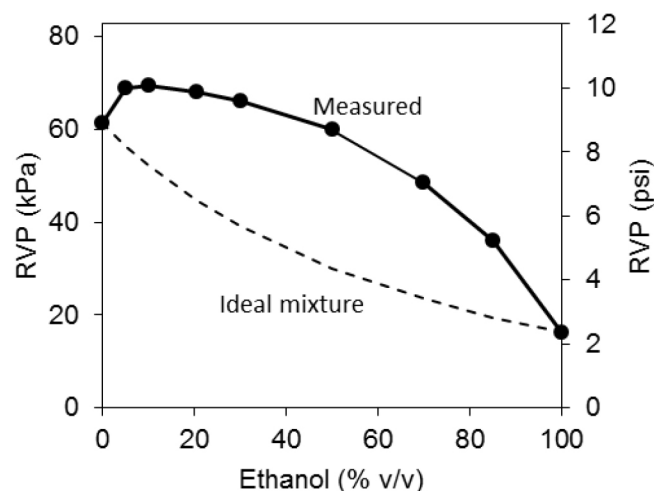


Figure 5. Reid vapor pressures (predicted Dry Vapor Pressure Equivalent) for ethanol-gasoline blends and values for an ideal mixture [12].

As shown in Figure 5, when ethanol is added to gasoline, the blend exhibits a vapor pressure that is higher than that of both the gasoline and ethanol portions of the blend. Note that the highest RVP was observed when 10% v/v ethanol is added. Further increasing ethanol content reduces the RVP, such that RVPs match that of the base gasoline at ethanol concentrations of 30% to 55% v/v, with higher concentrations needed for base gasolines with lower RVP [11, 12, 13].

This non-intuitive behavior is a consequence of molecular interactions between the gasoline components and ethanol. For an ideal mixture of components, vapor pressure would follow a molar concentration weighting (dashed line in Figure

5). In ethanol-gasoline blends, the nonpolar (even distribution of electron charge) hydrocarbon molecules in gasoline interfere with the intermolecular hydrogen bonding between the polar (uneven distribution of electron charge, creating positive and negative poles) ethanol molecules, and the ethanol interferes with molecular interactions between the gasoline hydrocarbons [9,10,15]. These interferences with intermolecular bonding allow the respective molecules to more readily escape the liquid as vapor, increasing vapor pressure, and result in formation of near-azeotropes of ethanol and gasoline components. For a true azeotrope, the relative concentrations of the components in the vapor are the same as those in the liquid mixture. In other words, a true azeotropic mixture vaporizes as if it were a single component. While ethanol-gasoline blends are not true azeotropes, the volatility characteristics are affected in a near-azeotropic manner.

An extensive set of data illustrating vapor pressure behavior for ethanol blends with market gasolines and blendstocks of varying volatility is provided in a study by the American Petroleum Institute (API) [11]. The RVP increase with ethanol addition to gasoline was shown to be dependent on the composition of the gasoline, with greater RVP increase observed for gasoline with lower RVP or greater saturated hydrocarbon content. In that study, the RVPs of E10 blends was nearly always greater than or equal to the RVP of E12.5, E15, E20, and E30 with the same blendstock.

The fuel components that contribute most to the vapor pressure are the most volatile gasoline components, primarily isomers of butane and pentane, plus ethanol when present. Vapor pressure increases with temperature, and the vapor pressure of ethanol-gasoline blends shows a greater change with temperature than gasoline containing no ethanol [12]. Thus, for E0 and E10 fuels with the same RVP, the E10 will have an increasingly higher vapor pressure than the E0 as temperature is increased above the RVP temperature (37.8°C). Likewise, the E10 will have a lower vapor pressure than the E0 at lower temperatures.

Distillation Curve

The normal boiling point of ethanol is 78°C, and it might be expected that the ethanol in an ethanol-gasoline blend would distill at this temperature. However, distillation in this test method does not occur as discrete segments of compounds being distilled; rather it represents vaporization of mixtures with gradually varying composition and with decreasing volatility. As with the vapor pressure, the near-azeotropic behavior of an ethanol-gasoline blend affects the distillation characteristics for portions of the distillation curve [12,16]. An extensive set of data illustrating distillation curve behavior for ethanol-gasoline blends with gasoline blendstocks of varying volatility (ASTM D4814 Class AA to Class E) is provided in the study by API [11]. As an illustration of this behavior, the typical response of the distillation curve as ethanol content is varied is shown in Figure 6 for a certification gasoline blendstock [16].

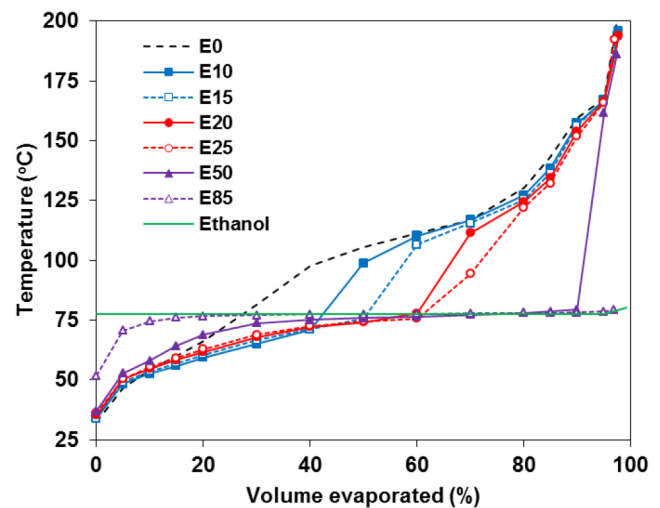


Figure 6. Distillation curves for ethanol-gasoline blends [16].

In Figure 6, the near-azeotropic behavior of the ethanol-gasoline blends is visible as a more slowly rising curve with higher volatility than that of the base gasoline (i.e., a greater volume distilled at a given temperature). For increasing ethanol content, this slowly rising curve expands to cover a larger portion of the distillation curve. Note in Figure 6 that T10 and T90 values (the temperature at which 10% and 90% of the fuel volume has distilled, respectively) are only slightly affected for ethanol-gasoline blends up to E25, whereas T50 decreases significantly from E0 to E15. Note also that the fraction of fuel evaporated at 100 °C increases substantially as ethanol content is increased.

ASTM D4814, the Standard Specification for Automotive Spark-Ignition Engine Fuel [18], specifies limits on T10, T50, and T90 which depend on the volatility class of the fuel. ASTM D4814 also specifies limits on the driveability index, which is defined by equation 1:

$$\text{Driveability Index} =$$

$$1.5 \text{ T10} + 3.0 \text{ T50} + 1.0 \text{ T90} + 1.33 \times \% \text{v ethanol}$$

(1)

This equation was based on a study of vehicle driveability conducted at ambient temperatures of -1°C to 4°C (30° to 40° F) for ethanol blends of 3%, 6%, and 10% by volume ethanol using 2002 and 2003 MY vehicles [19]. This temperature range was chosen because it corresponded to the temperature below which enrichment was used to improve driveability for production vehicle calibrations at that time. Note that this equation was developed for ethanol blends up to E10, and therefore may not be relevant for higher ethanol blends or for later model year vehicles with more sophisticated engine control strategies.

KNOCK LIMIT

It is well known that blending ethanol in gasoline provides a large improvement in knock resistance. This is a



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consequence of three knock-related properties of ethanol: RON, sensitivity, and HoV [20]. Ethanol's RON value of 109 provides high inherent or chemical knock resistance; the high sensitivity of ethanol results in longer autoignition delay time and greater knock resistance as combustion phasing is retarded due to reduced unburned gas temperature; and the high HoV of ethanol results in substantial cooling of the charge, especially with DI. Further, the effect of charge cooling on reducing the rate of autoignition kinetics is amplified by the high sensitivity of ethanol [20,21]. (Lower temperature provides a greater benefit in knock resistance with a high sensitivity fuel).

Vehicle calibrations of production gasoline engines retard spark timing from the thermodynamic optimum timing (Minimum spark advance for the Best Torque, or MBT) at high load to avoid knock, resulting in retarded combustion phasing. This is especially pronounced for turbocharged gasoline engines, which run with very retarded combustion phasing at low speed-high load. Therefore, the improvement in knock resistance at retarded combustion phasing with ethanol has a large impact on the full load torque for a turbocharged gasoline engine.

Example data are shown in Figure 7 for a boosted single cylinder direct injection engine [20]. For these data, inlet pressure was swept at constant engine speed, and spark timing was set to borderline knocking at each inlet pressure. The resulting combustion phasing, as measured by the location of 50% mass fraction burned in degrees aTDC (CA50), is plotted as a function of the 720°C-CA-based Net Mean Effective Pressure (NMEP). As shown in this figure, the improvement in knock-limited NMEP as ethanol content is increased is much greater at retarded combustion phasing than at the thermodynamic optimum MBT combustion phasing [20].

The increase in knock-limited torque with increasing ethanol content can be limited by the available boost pressure of the turbocharger system and the peak pressure capability of the engine structure, especially at high ethanol content. An example of multi-cylinder data for a gasoline turbocharged direct injection (GTDI) engine is shown in Figure 8, which is a comparison of knock-limited brake mean effective pressure (BMEP) and brake thermal efficiency (BTE) vs. engine speed for 91 RON E0 gasoline and E85 [22,23]. For this engine, the BMEP with E85 below 2250 rpm is limited by the available boost provided by the turbochargers, and above 2250 rpm by the turbine inlet temperature constraint of 950°C and the peak cylinder pressure (mean plus three sigma) constraint of 150 bar. The BMEP with 91 RON E0 gasoline is limited by knock at all engine speeds and by the turbine inlet temperature constraint above 2250 rpm at stoichiometry ($\lambda = 1$) and above 3000 rpm with enrichment ($\lambda = 0.8$).

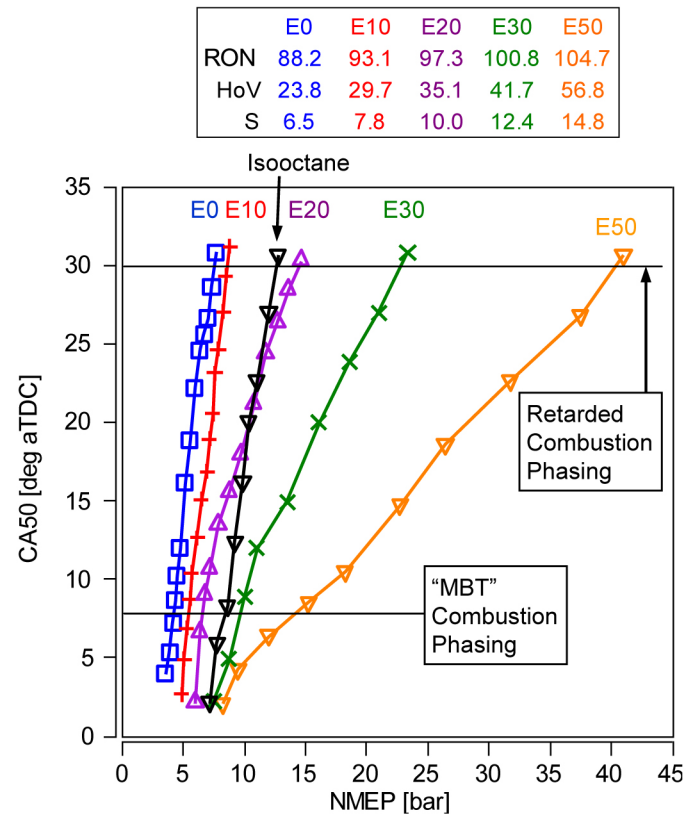


Figure 7. CA50 vs. NMEP for 88 RON blendstock at 1500 rpm and stoichiometry in a single-cylinder engine at 10:1 CR with DI [20].

For the data set of Figure 8, peak BMEP with 91 RON E0 gasoline is 18 bar at stoichiometry and 23 bar with enrichment compared to 32 bar with E85 at stoichiometry. BTE is higher for E85 than for gasoline at stoichiometry due primarily to combustion phasing which is closer to optimum. BTE is significantly degraded when the E0 gasoline is run with enrichment to improve full load BMEP. Improved efficiency at high load with increasing ethanol content of the fuel is discussed in more detail in a later section of this paper.

The increased knock resistance of ethanol blends is best utilized in boosted engines as described above; however, it is also advantageous in naturally aspirated engines. In a study by GM [24] on a naturally aspirated DI engine, knock-limited BMEP at full load was increased by 13-15% with E85 compared to a customer intent 87 AKI E0 gasoline. These performance gains were enabled by the increased knock resistance of E85 which allowed optimum combustion phasing, by increased volumetric efficiency due to the higher HoV and consequent charge cooling of E85, and by improved indicated efficiency due to lower burned gas temperatures (discussed in more detail later in this paper).