

Blending Octane Number of Ethanol in HCCI, SI and CI Combustion Modes

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ABSTRACT

The effect of ethanol blended with three FACE (Fuels for Advanced Combustion Engines) gasolines, I, J and A corresponding to RON 70.3, 71.8 and 83.5, respectively, were compared to PRF70 and PRF84 with the same ethanol concentrations, these being 2%, 5%, 10%, 15% and 20% by volume. A Cooperative Fuel Research (CFR) engine was used to understand the blending effect of ethanol with FACE gasolines and PRFs in spark-ignited and homogeneous charge compression ignited mode. Blending octane numbers (BON) were obtained for both the modes. All the fuels were also tested in an ignition quality tester to obtain Blending Derived Cetane numbers (BDCN). It is shown that fuel composition and octane number are important characteristics of all the base fuels that have a significant impact on octane increase with ethanol. The dependency of octane number for the base fuel on the blending octane number depended on the combustion mode operated. The aromatic composition in the base fuel, effects blending octane number of the mixture, for fuels with higher aromatic content lower blending octane numbers were observed for ethanol concentration.

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INTRODUCTION

Ethanol has a research octane number (RON) 108 [1]. This is higher than gasoline, which is typically RON 92 to 97 [2]. Ethanol has been widely accepted as a transportation fuel either in its pure form or in a blend with gasoline. Ethanol acts as an octane enhancer and its addition to gasoline helps to increase the mixture's octane number and thereby reduce tendency to knock [3]. It has been indicated that the use of ethanol in conjunction with a gasoline helps to increase the engine efficiency, torque and power compared to the baseline gasoline [4].

Global increasing energy demand and the forthcoming stringent emission regulations require high efficiency and low emissions for future combustion engines. Raising the octane rating of the fuel can enable to higher compression ratios and boost levels giving lower fuel consumption [5]. The utilization of a biofuel such as ethanol together with gasoline can help to solve energy security problems.

Today many gas stations in the US have started to offer ethanol as an oxygenated gasoline blend fuel, and it is not unusual to provide E85 in the form of 85% ethanol and 15% gasoline [6]. In Brazil, all cars run on either 22% or 25% ethanol-gasoline blend or pure ethanol [6]. In Sweden gasoline containing 5% ethanol and in Australia gasoline containing 10% ethanol is used by transport vehicles [7]. Stein et al

studied ethanol gasoline blends of E20-E40 and in another study E85 [8,9]. The Lower Heating Value (LHV) of ethanol is less than of gasoline (40 MJ/kg), hence volumetric fuel consumption (l/kWh) will be higher for the same engine efficiency [10]. On the other hand high heat of vaporization for ethanol results in high compression ratios through improved knock mitigation.

It has been found that RON increases with ethanol blending but the effect is diminished at approximately 30% ethanol by volume where the RON starts to have a constant value and eventually converges to the RON of neat ethanol [11]. A small quantity of ethanol can lead to significant rise in the RON of the blend [1,12]. Anderson et al highlighted that 10% of ethanol addition caused a significant increase in the RON of the blend [13]. It was also highlighted that the base fuel with low RON had the greatest increase in RON with 10% ethanol addition [13]. Rankovic et al reported similar observations [12]. The aromatic content in the base fuel has significant effect on the RON response, and it has been identified that the addition of aromatics will cause a decrease in the RON response with the addition of ethanol [14]. The blending of ethanol with gasoline causes a non-linear increase in the RON and non-linearity depends on the composition of the base fuel [12,14]. Foong et al investigated ethanol blended with PRF91 and with a non-oxygenated RON91 gasoline [11]. The response for PRF91 was found to be more nonlinear than the

RON91 gasoline, highlighting that the composition of base fuel plays an important role in the non-linear RON response [1]. The non-linearity gives rise to a blending octane number. Blending octane number have been previously used to understand the nonlinear nature of base fuel blended with ethanol [12]. The blending octane number is expressed as a function of base fuel composition, blending RON and the RON of the base fuel. For smaller quantities of octane boosters, the blending octane number is higher. The blending octane number decreases and finally approaches the same number as that of the additive at 100% concentration.

There have been many experiments performed using lower octane fuels at low engine loads and higher octane fuel for high engine loads [7,8,15,16,17,18,19,20,21]. Viollet et al found that a low octane naphtha fuel (RON 61) enabled maximum brake torque (MBT) spark timing to be attained at low engine loads. At medium to high engine loads, MBT spark timing could still be maintained by adding higher RON oxygenated fuel [10]. The combination of a high and low RON fuel in separate tanks to create fuels of the required octane rating according to demand can be considered as the 'Octane-on-Demand' concept [10]. Daniel et al used ethanol to investigate the concept of double fuel injection and found that a greater degree of engine downsizing could be obtained relative to gasoline [17]. Bourhis et al investigated the viability of implementing Octane-on-Demand using a low RON naphtha fuel in conjunction with several high octane boosters [19]. Ethanol was shown to provide the greatest benefit in terms of RON boosting. Wang et al also investigated the double fuel concept by comparing the effect of fuel delivery pathway on engine performance [15]. In this case, both gasoline and ethanol were delivered to the engine using Port fuel injector (PFI) and direct injector (DI). Each combination provided fuel economy benefits, but the thermal efficiency was higher in the case where the ethanol was injected directly into the engine. This was attributed to the high latent heat of vaporization of ethanol and additional charge cooling benefits. Ojapah et al compared the performance, combustion process and emissions between four operating modes with gasoline and its blend with ethanol, E15 and E85 [22]. It was highlighted that multiple fuel injections and higher injection pressure can lead to reduction in the fuel consumption.

Another promising combustion concept that has received attention is Homogeneous Charge Compression Ignition (HCCI). The HCCI combustion is appreciated because it provides low nitric oxides (NO_x) emissions and improved fuel economy [23,24]. In spark ignition (SI) engines, RON has been used to describe the anti-knock quality of the fuel [25]. Nonetheless, the RON cannot be used as an ideal parameter to describe the autoignition properties of the fuel in the HCCI combustion mode [24,26,27]. Recently the Lund-Chevron HCCI fuel number was proposed to better describe the autoignition properties of the fuel [26]. Similar values for RON and HCCI fuel number were found for the blends of ethanol, iso-octane and nheptane at low inlet air temperatures. But at high inlet air temperatures, the RON and HCCI numbers did not match well [26]. This suggests that similar non-linear effects will occur with ethanol addition for both SI and HCCI combustion modes at low inlet temperatures. The addition of toluene in the blends of ethanol, isooctane and n-heptane also showed

that the RON and HCCI numbers do not match well both for low and high inlet air temperatures [26]. The concept of dual fuel injection has also been applied in HCCI combustion mode [28, 29, 30].

Compression ignition engines have been recognized as one of the most fuel efficient engines mainly due to high compression ratios and reduced throttling losses [31]. Ethanol has been considered as an alternative fuel for diesel engine in the form of ethanol-diesel blends [32]. The maximum amount of ethanol that can be added to the diesel depends on properties such as blend stability, viscosity and lubricity, energy content, material compatibility and cetane number [32].

It has been previously found that the aromatics molecules present in gasoline offers the greatest knock resistance [2]. The study will address the role of base fuel composition and octane number in the RON evolution with ethanol addition. FACE I has a RON of 70.3 and FACE J has a RON of 71.3 but the aromatic concentration for both of them differs by about 30%. This enabled a test of how ethanol will increase octane number with a base fuel with low or high aromatic contents. As a reference PRF70 was also used with 0% aromatic.

A Cooperative Fuel Research (CFR) engine in both SI and HCCI combustion mode was used to conduct the experiments with ethanol-FACE gasoline blends and ethanol-PRF blends. Ethanol with a RON 108 was selected as the octane booster. Three low RON gasolines, FACE (Fuels for Advanced Combustion Engines) A, FACE I and FACE J were selected as base fuels. Detailed information on the FACE fuels properties can be found in the report published by Coordinating Research Council [33]. The fundamental ignition and heat release characteristics of FACE gasolines have been previously investigated [34,35,36,37,38]. Ethanol with concentration by volume of 2%, 5%, 10%, 15% and 20% was added to the FACE fuels and two PRF solutions of RON 70 and RON 84.

For SI combustion, the CFR was operated at RON conditions that correspond to engine speed of 600 rpm, air inlet temperature of 52 °C and spark timing (ST) of -13 CAD (Crank Angle Degree). For HCCI mode the engine was operated with four conditions as shown in Table 1.

The operating conditions HCCI-1 (600 rpm, 52°C) and HCCI-4(900 rpm, 149°C) were chosen to compare with RON and MON conditions in SI conditions. That involved simultaneously changing two variables (speed and temperature). The other two HCCI numbers were chosen to see the effect of changing each variable individually resulting in four HCCI numbers. Recent work by Truedsson et al also supported the selection of four HCCI numbers [26]. Five blending octane numbers (BON) corresponding to four HCCI fuel numbers and one RON number were obtained. An Ignition Quality Tester (IQT) was also used to obtain the blending derived cetane numbers (BDCN) for all the ethanol-FACE fuels and ethanol-PRF blends.

Table 1. Four HCCI fuel numbers

HCCI fuel numbers	Engine speed (rpm)	Intake air Temperature $T_{in}(^{\circ}\text{C})$
HCCI-1 (RON)	600	52
HCCI-2	600	149
HCCI-3	900	52
HCCI-4 (MON)	900	149

EXPERIMENTAL SET UP

A Waukesha variable compression ratio cooperative fuels research (CFR) engine was used for the experiments and operated in SI and HCCI mode. Figure 1 shows the CFR engine used for experiments. The range of compression ratio was from 4 to 15.5 with a resolution of 0.1. The carburetor of the standard CFR engine was replaced with a port injection system. The intake air flow was measured by Elster mass flow meter. The air temperature was regulated by an air heating system which consists of three ceramic heating clamps each 400 W. A thermocouple 3.5 cm upstream of fuel injector is used to measure the intake air temperature. ETAS lambda sensor was used to determine the equivalence ratio. The fuel was injected into the hot air flow with a feed fuel pressure of 6 bars. The fuel flow rate was calculated with the measured lambda and the air flow rates. An AVL GH14 D pressure transducer mounted on the cylinder was used to extract the information about the in-cylinder pressure sampled with 0.1 CAD. No modifications were done to the original water cooling system. The water temperature was 95° C. The operating conditions of the CFR engine are presented Table 2.

Table 2. Engine specifications and operating conditions

Engine Type	Single Cylinder CFR
Injection System	Port Fuel Injection
Bore	82.55 mm
Stroke	114.3 mm
Connecting Rod	254 mm
Compression ratio	Variable from 4:1 to 15:1
Speed	600-900 rpm
Spark timing (ST)	-13 CAD (Crank Angle Degree)
Minimum Intake Air Temperature	52 ± 2 °C
Maximum Intake Air Temperature	149 ± 2 °C
Lambda (λ)	1(SI) or 3(HCCI)

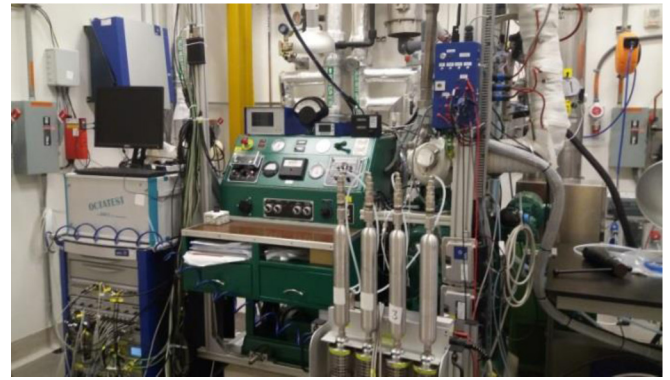


Figure 1. CFR engine

IQT-Experiment

The IQT is a standard test device to measure derived cetane number (DCN) according to ASTM D6890 [39]. The IQT is equipped with a constant volume combustion chamber of volume 0.21 L that is filled with zero air ($20.9 \pm 1.0\%$ O₂ and 79% Nitrogen with negligible amounts of hydrocarbons and water) pressurized to 2.137 ± 0.007 MPa and heated to a standard temperature as explained below. Figure 2 shows the ignition quality tester. The standard temperature is determined by adjusting the temperature so 3 runs of n-heptane provides an ignition delay of 3.78 ± 0.01 ms. Ignition delay of fuels is then measured from the pressure trace obtained by injecting a liquid fuel into pressurized and heated air. An IQT is ideally designed to measure ignition of diesel-like (high reactivity) fuels, however for gasoline-like (low reactivity) fuels, the gradient method described in can be applied [40]. All ignition delay values in the present study are obtained with the gradient method. The method is based on the pressure signal. It involves the determination of the point of intersection of two line tangents (LT): one LT at the pressure recovery point, the point where the pressure regains initial chamber pressure that dropped due to evaporative cooling; the other LT being the maximum slope during combustion pressure rise [40].

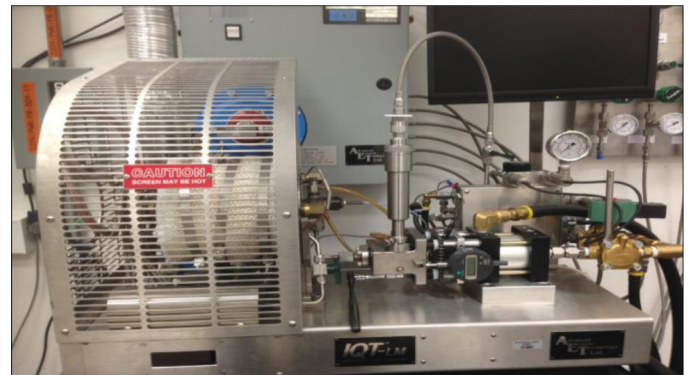


Figure 2. IQT apparatus

Fuels

Three FACE (Fuel for advanced combustion engines) gasolines, specifically FACE I, FACE J and FACE A were used for the study. Details on some of the properties and the concentration of aromatics and n-paraffin's in the FACE fuels are given in Table 1. The mixtures corresponding to RON of 70 and 84 were also tested.

Ethanol with concentration by volume of 0%, 2%, 5%, 10%, 15% and 20% was added to the FACE fuels and PRF. The total fuel blends for FACE gasolines and PRF solutions were 18 and 12, respectively. In total, 30 blends were tested in SI, HCCI and in IGT. More details about the fuel blends can be found in [Appendix-A](#).

Table 3. FACE Fuels and their properties

Fuel Designation	FACE I	FACE J	FACE A	PRF 70	PRF 84
RON	70.3	71.8	83.5	70	84
MON	69.6	68.8	83.6	70	84
Sensitivity	0.7	3.0	-0.1	0	0
Aromatic (%)	5.0	35.0	5.0	0	0
N-Paraffin's (%)	5.0	25.0	5.0	30	16

OCTANE NUMBER (ON) OF BLENDS

Research Octane Number

The Research and Motor octane number (RON and MON respectively) are used to characterize the autoignition properties of the fuel in the SI engines [25]. The scale of RON and MON are based on two paraffinic hydrocarbons: Iso-octane defines the maximum limit of the scale with a value of 100, and n-heptane defines the minimum limit of the scale with a value of 0 [25]. Although, it is possible to have fuels beyond 100 octane number. For fuels with octane numbers above 100, the scale is extrapolated through the addition of dilute tetraethyl lead (TEL) to iso-octane based on an empirically determined relationship [41]. This extends the octane number scale to its maximum value of 120.3. Blends of iso-octane and n-heptane are referred to as primary reference fuels (PRFs). A PRF65 refers to RON of 65 with iso-octane percentage of 65% and 35% of n-heptane by volume. The RON and MON are measured in a standardized single cylinder Cooperative Fuel Research (CFR) engine using ASTM standard tests [41,42]. The RON is obtained by running the CFR at 600 rpm, with an inlet air temperature of 52°C and constant spark timing of 13° before top dead center (bTDC). The compression ratio is adjusted until trace knock is detected. Since the CFR engine for this study was modified, RON for the fuel blends were obtained by determining the transfer function for PRFs ranging from 70 to 100. The transfer function for this study is defined as the conversion procedure of the compression ratio readout to the mixture of iso-octane and n-heptane. [Figure 3](#) show the compression ratio for trace knock obtained in SI combustion mode with PRFs. [Figure 4](#) illustrates the procedure followed to obtain the compression ratios for different PRF mixtures for the transfer function in the SI mode. A knock criteria of peak to peak pressure fluctuations of 2 bar $\pm$ 0.02 for a moving window of 188 cycles was set to determine the compression ratio. For all fuel blends, the compression ratio was adjusted until peak to peak pressure fluctuation of 2 bar was obtained. A lambda sweep was then performed to confirm that the lambda for maximum knock was used.

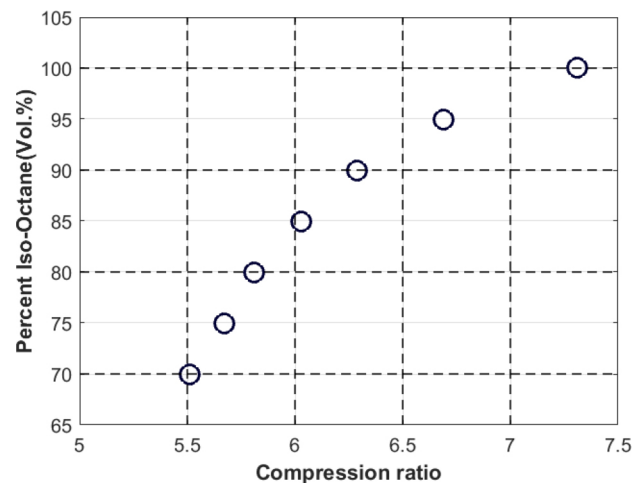


Figure 3. Transfer function in SI mode, 600 rpm, 52°C, ST=-13, $\lambda=1$

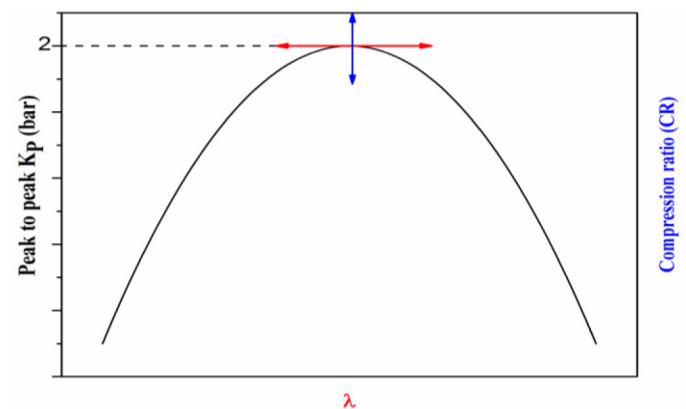


Figure 4. Knock criteria (K p) for compression ratio

A line of fit in the form of quadratic was obtained from [Figure 3](#). The equation was in the form:-

$$RON = aR_c^2 + bR_c + c \quad (1)$$

Where RON represented the percentage of iso-octane by volume in the Primary reference fuel mixture and R_c was the compression ratio. The coefficients of the equations were a , b and c and their constant values are given in [Appendix A](#) in [Table A3](#). The fuel blends were tested and the compression ratio obtained was used in [equation 1](#) to estimate RON of the fuel blends.

Homogeneous Charge Compression Ignition (HCCI) Fuel Number

It was identified that RON and MON are not sufficient to characterize the auto-ignition behavior of the fuel in HCCI operating conditions [26]. The Lund-Chevron HCCI number was developed to understand the auto-ignition behavior of the fuel in HCCI mode [26]. The procedure for determining HCCI fuel numbers requires finding the compression ratio for the auto-ignition of tested fuel with a CA50 (Crank Angle for 50% heat release) of 3° after TDC. Similar to SI mode, a transfer function plot was obtained by autoigniting different mixtures of Primary Reference Fuels (PRFs). [Figure 2](#) shows the obtained transfer function for all the four HCCI conditions.

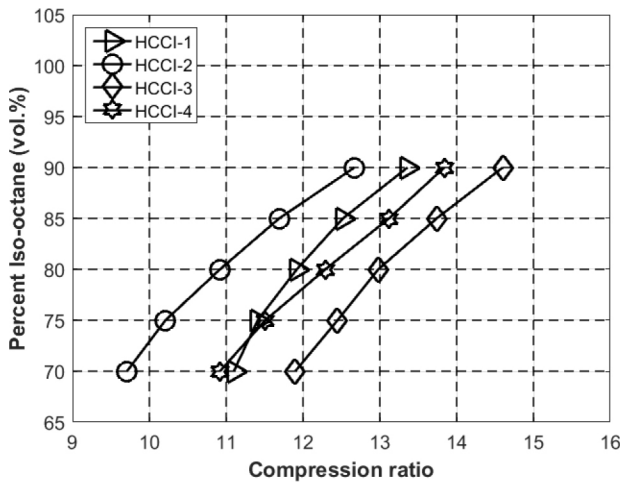


Figure 5. Transfer function in HCCI mode for four HCCI operating conditons, $\lambda=3$

A line of best fit was obtained for all the four conditions. The line of best fit was in the form of quadratic equation given by:-

$$HCCI \text{ fuel number} = pR_c^2 + qR_c + r \quad (2)$$

Where *HCCI fuel number* represented the percentage of iso-octane by volume in the Primary Reference Fuel mixture and R_c was the compression ratio. The coefficients of the equations were p, q and r and their constant values are given in Appendix A in Table A4. The FACE fuel blends were tested in HCCI mode and the required compression ratios for the autoignition of the blends were used alongside equation 2 to estimate the HCCI fuel number.

Blending Octane Number (BON)

The non-linear response of RON with ethanol addition has given rise to the so-called blending octane number. The octane number of ethanol is 108 and if there were no non-linear effects, then the blending octane number would be constant and equal to the pure component octane number [1]. A higher blending octane number means that on a per unit volume basis, the ethanol provides more anti-knock resistance.

The blending octane number (BON) was expressed in terms of base fuel RON (for the present study, FACE fuels and PRF solutions at 0% ethanol), the concentration of the base fuel, the booster concentration (for the present study, ethanol) and the blending RON(BRON) [1,12]. For the case of SI mode, BON can be expressed as:

$$RON_{base} \cdot C_{base} + BON \cdot C_{booster} = RON_{mix} \quad (3)$$

Where

RON_{base} = RON of the base fuel

C_{base} = Concentration of the base fuel

$C_{booster}$ = Concentration of the booster

RON_{mix} = Octane numbers of the blends (2%,5%,10%,15%,20%vol.)

For HCCI mode, equation 3 can be expressed as:-

$$HCCI_{base} \cdot C_{base} + BON \cdot C_{booster} = HCCI_{mix} \quad (4)$$

Where

$HCCI_{base}$ = HCCI fuel number for the base fuel (0% ethanol)

C_{base} = Concentration of the base fuel

$C_{booster}$ = Concentration of the booster

$HCCI_{mix}$ = HCCI fuel numbers of the blends (2%, 5%, 10%, 15%, 20%vol.)

Blending Derived Cetane Number (BDCN)

Derived cetane number (DCN) of the fuel samples are calculated based on the ignition delay range; i.e., for values of 3.1 to 6.5 ms equation 5 is used [40], while for values outside this range eq.6 is used [40]

$$DCN = 4.46 + \left(\frac{186.6}{\tau_{id}} \right) \quad (5)$$

$$DCN = 83.99[(\tau_{id} - 1.512)^{-0.658}] + 3.547 \quad (6)$$

Where

τ_{id} = Total ignition delay time

For CI mode, equation 3 can be expressed as:-

$$DCN_{base} \cdot C_{base} + BDCN \cdot C_{booster} = DCN_{mix} \quad (7)$$

Where

DCN_{base} = Derived Cetane Number for the base fuel (0% ethanol)

C_{base} = Concentration of the base fuel

$C_{booster}$ = Concentration of the booster

DCN_{mix} = Derived Cetane Number of the blends (2%, 5%, 10%, 15%, 20%vol.)

$BDCN$ = Blending Derived Cetane Number

RESULTS

SI Results

FACE I, FACE J and FACE A

The three FACE fuels were blended with ethanol and tested in the modified CFR engine. Ethanol with concentration by volume of 2, 5, 10, 15 and 20 percent was added to the FACE fuels. Figure 6 and 7 shows the compression ratio and the change in the RON of the three FACE fuels with the ethanol addition.

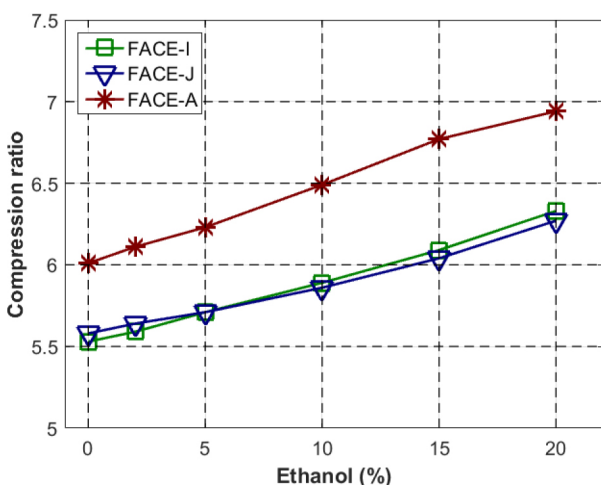


Figure 6. Compression ratios for FACE fuels in SI mode, 600 rpm, $T_{in} = 52^{\circ}\text{C}$, $ST = -13$ CAD, $\lambda = 1$

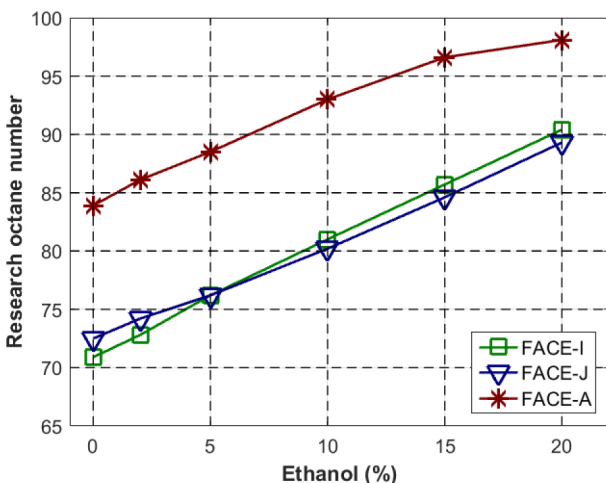


Figure 7. RON of FACE I, J and A with ethanol concentration in SI mode, 600 rpm, $T_{in} = 52^{\circ}\text{C}$, $ST = -13$ CAD, $\lambda = 1$

The results show that the RONs of FACE I and FACE J changed from around 70 to 90 and were linearly varying with the addition of ethanol up to the maximum tested 20%. The blending RON for FACE I blends (5% aromatics) are slightly lower for 2% ethanol when compared with FACE J (35% aromatics). However, beyond concentration of 5%, the blending RON for Face I is slightly higher. This is consistent with the findings of Silva et al which showed that blends with low aromatic contents (9% vs 43%) had significantly higher blending RON with 25% ethanol addition [43]. The change in RON for FACE A was from 84 to 97 with 20% ethanol addition. The RON of FACE A blends increased linearly up to concentrations of

10% ethanol. However, beyond concentrations of 10% ethanol the RON behavior became saturated. Foong et al also observed near-saturated behavior for gasoline blends with high ethanol concentrations [44].

Figure 8 presents the blending octane number for three FACE fuels with the addition of Ethanol. The BON was higher than the RON of pure ethanol and hence non-linear effects are present. The blending octane number for all three FACE fuels was in the range of 140 to 200. The three FACE fuels were observed to behave non-linearly with the increasing ethanol concentration. The octane enhancement effect of ethanol on FACE I was lower at 2% ethanol and then rather constant from 5 to 20%. The octane enhancement effect on FACE J was lowest for ethanol concentrations of 2 to 15% due to the higher aromatic contents of the base fuel. A decaying behavior with the increase of ethanol concentration was observed for FACE A which has a higher base RON. The BON behavior for FACE I and FACE A is similar between 5% and 15% ethanol concentrations followed by a sharp decrease for FACE A after 15%. Rankovic et al have shown that for the base fuel with RON 71 and 91, the BON behaved differently and higher BON was observed for RON 71 base fuel [12]. Both FACE I and FACE A have 5% aromatic concentration but FACE A has RON of 83.5 higher than FACE I which has a RON of 70.3, so it was expected that BON behavior will be different. It is difficult to conclude that BON does not depend on octane number of the base fuel, but it could be the case that FACE A with RON 83.5 is not sufficient to indicate the dependency of octane number on BON as previously highlighted by Rankovic et al [12].

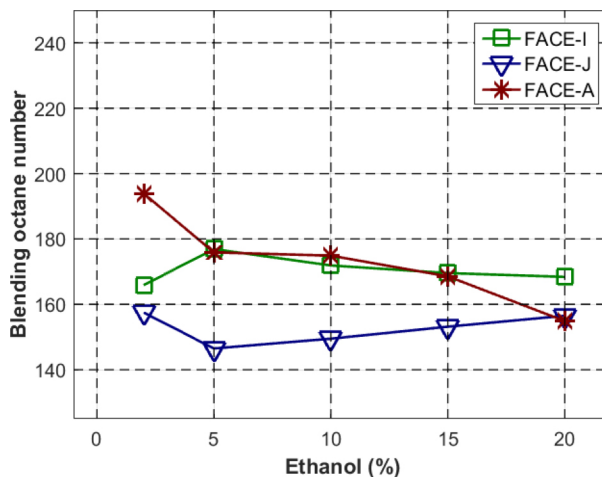


Figure 8. Blending octane number for FACE I, J and A with ethanol concentration in SI mode, 600 rpm, $T_{in} = 52^{\circ}\text{C}$, $ST = -13$ CAD, $\lambda = 1$

HCCI Results

FACE I, FACE J, FACE A, PRF70 and PRF84

In addition to the three FACE fuels, PRF70 and PRF84 were also tested in HCCI mode. FACE I and FACE J had a RON close to 70, and therefore PRF70 was blended with ethanol for comparison purposes. The same applies for the selection of PRF84 which is close to the RON of FACE A. As discussed in previously, the RON is not

an ideal indicator of the fuel autoignition characteristics for HCCI operating conditions. As such, the HCCI fuel number will be used to describe the performance of FACE fuels and PRFs in this section

Figure 9 presents the variation of HCCI fuel number-1 with ethanol concentration for an engine speed of 600 rpm and inlet air temperature of 52° C corresponding to RON conditions. HCCI-1 in the legend is used to show the operating condition in HCCI mode in terms of speed and inlet air temperature. More details about the definition of four HCCI numbers specifically defined for this study can be found in the introduction section. For neat ethanol, the HCCI number will be equal to the RON of the fuel as mixtures of iso-octane and n-heptane are used to define the scale in both cases. For ethanol concentrations up to 5%, it can be observed that the change in the HCCI number is approximately the same for all FACE fuels. Among the low RON fuels, FACE J had a slightly different slope than FACE I and PRF70.

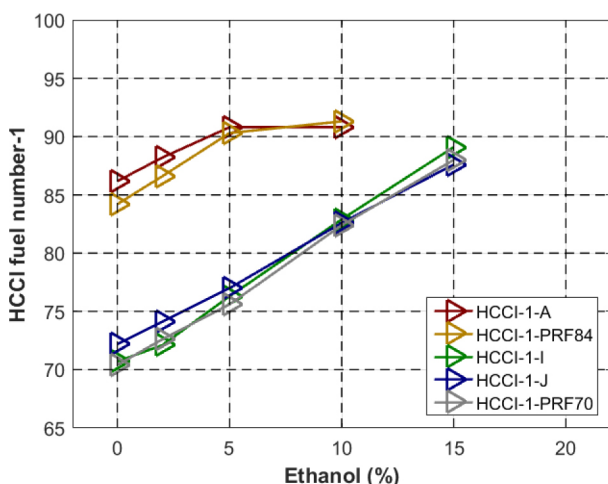


Figure 9. HCCI fuel number for FACE fuels, PRFs at 600 rpm, $T_{in} = 52^{\circ}\text{C}$ and $\lambda=3$

Figure 10 presents the blending octane numbers for all three FACE fuels and PRF70 and PRF84. The overall BON level for the low octane fuels was 140 to 190. The blending octane numbers for FACE I, FACE J and PRF70 were observed to be lower than FACE A and PRF84 at low ethanol concentrations but with the increasing concentration, a sharp decrease in the BON for FACE A and PRF 84 occurred.

It was observed that FACE J with a higher aromatic content has a lower BON than FACE I. This trend is consistent with the SI tests (Figure 8). Overall, ethanol had a strong octane enhancement effect on the fuels with high RON at low ethanol concentration, e.g. FACE A and PRF84. The BON is in the range of 130 to 210 for the higher octane fuels (ON 84). The octane enhancement of ethanol on PRF84 was stronger than FACE A with the BON difference of about 20 units.

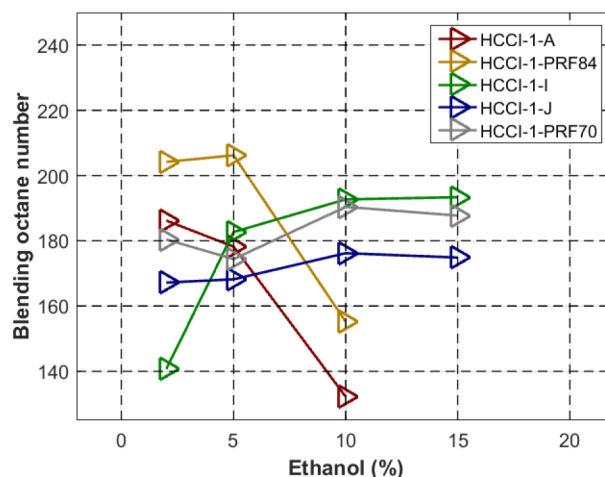


Figure 10. Blending octane number for FACE fuels, PRFs at 600 rpm, $T_{in} = 52^{\circ}\text{C}$ and $\lambda=3$

Figure 11 presents the plot of the BON when the engine speed was kept constant at 600 rpm, with an inlet air temperature increased to 149°C. The plot for HCCI fuel number for this case is presented in the Appendix B.

The overall BON level was in the range of 130 to 210. The BONs are more strongly influenced by the inlet air temperature than the engine speed. For the case of the 70 RON fuels, PRF 70 and FACE I showed somewhat a similar trend whereas FACE J had the lowest BON among the 70 RON fuels. Both FACE J and FACE I had RONs close to 70 but the plot shows a different octane enhancement effect for both fuels. This indicates that the fuel composition contribute towards the observed behavior.

Both FACE A and PRF84 exhibit large negative slopes similar to what was observed for an intake temperature of 52°C and speed of 600 rpm. A PRF84 had higher BON values than the other fuels for ethanol concentrations of up to 5%.

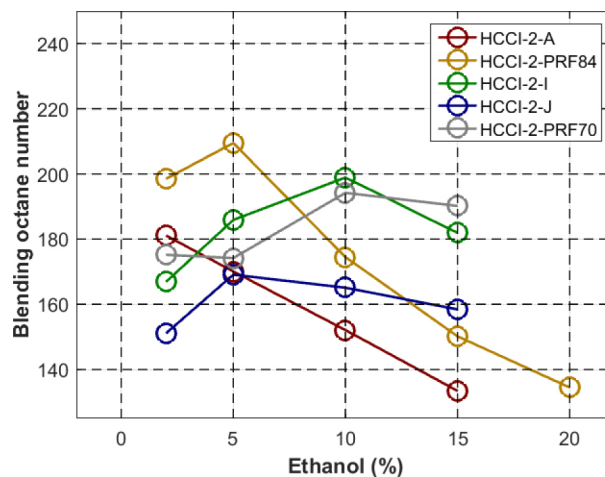


Figure 11. Blending octane number for FACE fuels and PRFs at 600 rpm, $T_{in} = 149^{\circ}\text{C}$ and $\lambda=3$

Figure 12 presents the plot of blending octane number when the engine speed was increased to 900 rpm with the inlet air temperature held constant at 52°C. The HCCI fuel number plot for this case is presented in Appendix B.

The overall BON level for the low octane fuel (ON 70) was 170 to 218. A PRF70 had a high blending octane numbers with up to 10% ethanol addition. The change in engine speed also has an improved octane enhancement effect on PRF70. It was observed that FACE J still has the lowest BON with the exception of 5% ethanol concentration. However, the limited number of data points for FACE A and PRF84 made it difficult to establish how the octane enhancement effect of ethanol will work for these high RON fuels with increasing ethanol concentration. The BON level for the high octane fuels was 165 to 190. However it can be observed that compared to the case when the engine speed was 600 rpm and inlet air temperature was 52°C, the octane enhancement effect of ethanol on FACE A and PRF 84 has weakened for all concentrations of ethanol. This effect was more considerably noticed for PRF84 than FACE A. This observation is not true for the case of FACE I and FACE J, which have shown an improvement in the BON as the speed is increased. Overall, the difference between the low octane and high octane number base fuels increase at an engine speed of 900 rpm.

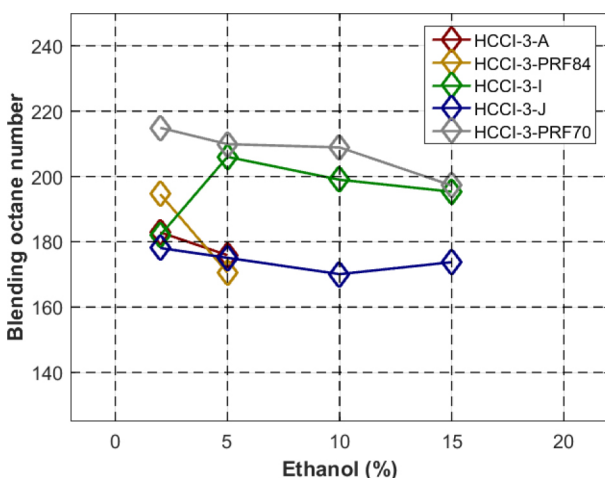


Figure 12. Blending octane number for FACE fuels and PRFs at 900 rpm, $T_{in} = 52^\circ\text{C}$ and $\lambda=3$

Figure 13 presents the combined effect of high intake temperature and engine speed, which corresponds to MON conditions of SI tests (900 rpm and 149°C respectively). The plot for HCCI number for this case is presented in Appendix B.

The overall BON levels for the low and high octane fuels were 160 to 240 and 110 to 250 respectively. Hence Figure 13 is using a different scale than Figure 10 to 12 for HCCI number 1 to 3. The combined effect of high engine speed and intake temperature suggests that ethanol was most effective for the low octane fuels. It can be observed that FACE I, FACE J and PRF70 had higher BONs in comparison with FACE A and PRF84, with the exception of low ethanol concentrations. The PRF 70 showed a positive slope at low ethanol concentrations followed by negative slope at high concentrations. At low concentrations of ethanol, PRF84 shows the highest BON. However, as ethanol concentration increases, this

enhancement effect is diminished. A particularly strong negative slope was observed for PRF84 while FACE A had the lowest BON values and the slope was also comparatively low. It could be noted that the blending octane number with 15% ethanol and FACE A as base fuel is reaching that of pure ethanol i.e. there is no longer any nonlinear blending effect of the ethanol.

It was observed that negative slope existed for high RON 84 fuels and positive or constant slope existed for the RON 70 fuels for all HCCI numbers except for HCCI-4 condition. That could be due to different ethanol effect on fuels with different base RONs. The slopes for the BON became steeper in the case of HCCI-4 compared to HCCI-1 which was expected because as the inlet temperature increases, ethanol becomes comparably more reactive, owing to its higher octane sensitivity [38]. The higher sensitivity results ethanol being less effective as an octane improver as the inlet temperature and in-cylinder temperature increase, and hence steeper slopes for BON were observed.

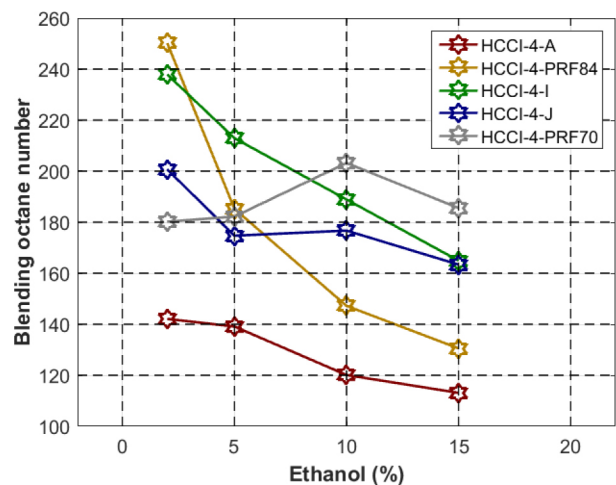


Figure 13. Blending octane number for FACE fuels and PRFs at 900 rpm, $T_{in} = 149^\circ\text{C}$ and $\lambda=3$

Effect of Speed and Temperature

The same data in Figure 10 to 13 will now be presented for one fuel at a time to see the effect of operating conditions such as engine speed and inlet air temperature more clearly. The previous section highlighted that the performance comparison for fuels with RON 70 (FACE I, FACE J, PRF 70) against fuels with RON 84 (FACE A and PRF84) at different engine speeds and inlet air temperatures. It was found that all the fuels did not behave the same. The engine speed and inlet air temperature were found to be critical in determining under which conditions ethanol will have the strongest octane enhancement effect.

Figures 14, 15 and 16 presents the BON for the FACE I, FACE J and PRF70 respectively. The HCCI fuel number plots for all three fuels are presented in the Appendix B.

The operating conditions had large effect on FACE I. At an engine speed of 600 rpm and intake temperature of 52°C, the BON for FACE I increases with the ethanol concentration. With the same engine speed of 900 rpm and inlet air temperature of 149°C, the BON goes