



Effects of Fuel Octane Rating, Ignition Timing, and Injection Timing on Idle Exhaust Emissions of Electronic Fuel-Injected Motorcycles Fueled with Gasoline–Ethanol Blends (E10 and E40)

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ABSTRACT

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This study investigated the combustion stoichiometry and exhaust emission characteristics of an electronically fuel-injected motorcycle operating under idle conditions. A $3 \times 2 \times 2$ full-factorial design generated 24 E10/E40 treatment combinations, supplemented by three E0 baseline conditions, resulting in a total of 27 operating conditions. Three gasoline grades (RON 90, RON 92, and RON 98), ignition timings of 3° and 7° before top dead centre (BTDC), and fuel injection timings of 350° and 355° after top dead centre (ATDC) were systematically evaluated. The measured parameters included the air-fuel ratio (AFR) and the concentrations of carbon monoxide (CO), hydrocarbon (HC), carbon dioxide (CO₂), and residual oxygen (O₂). CO emissions ranged from 0.57 to 7.27 vol.%, whereas HC emissions varied from 200.7 to 1,337.7 ppm. Compliance with the adopted idle CO and HC emission limits (CO < 3.0 vol.% and HC < 1,000 ppm) was achieved in 11 of the 27 operating conditions (40.7%). The most favorable operating condition was obtained using Gasohol E40 (RON 98) with an ignition timing of 3° BTDC and a fuel injection timing of 350° ATDC, producing 0.57 vol.% CO and 318.7 ppm HC. In contrast, the poorest emission performance was observed with Gasohol E10 (RON 90) at 7° BTDC and 355° ATDC, yielding 7.27 vol.% CO and 1,337.7 ppm HC. Most compliant operating conditions were associated with AFR values of approximately 14.0–15.5, CO₂ concentrations above approximately 11.6 vol.%, and residual O₂ concentrations generally below approximately 1.8 vol.%. Overall, the findings demonstrate that compliance with the adopted idle CO and HC emission limits depends on the coordinated optimization of fuel octane rating, ethanol blending ratio, ignition timing, and fuel injection timing.

1. INTRODUCTION

Recent technological developments in motorcycle engines have shifted from carburetor-based systems toward electronically controlled fuel injection (FI) systems. Compared with conventional carburetors, FI technology enables more precise regulation of the air-fuel ratio (AFR), resulting in improved combustion efficiency, lower fuel consumption, and reduced exhaust emissions [1, 2]. In FI engines, various sensors transmit operational data to the electronic control unit (ECU) for fuel and ignition control. The emergence of programmable ECU has further expanded calibration flexibility, allowing ignition timing and fuel injection timing maps to be modified according to specific operating requirements. Previous studies have demonstrated that such recalibration significantly influences carbon monoxide (CO) and hydrocarbon (HC) emissions in fuel-injected motorcycles [3]. For gasoline–ethanol (gasohol) blends, appropriate adjustment of ignition timing, injection timing, compression ratio, and fuel octane rating is required to maintain combustion stability and improve emission

performance [4, 5].

Previous studies have shown that injection parameters and combustion phasing strongly influence engine performance, combustion characteristics, and exhaust emissions [6]. Evidence from alternative-fuel engines further indicates that injection timing, compression ratio, air–fuel ratio, and fuel composition jointly affect ignition delay, flame propagation, combustion temperature, and emission formation [7]. Programmable engine management strategies have also been reported to improve combustion stability under varying operating conditions [8]. Gasohol blends have attracted considerable attention because ethanol possesses a high-octane number and inherent oxygen content, both of which contribute to improved combustion efficiency and lower CO and HC emissions under suitable operating conditions [9–11]. In Indonesia, commercially available gasoline grades include RON 90, RON 92, and RON 98, providing practical alternatives for gasoline–ethanol blending and engine calibration studies [12, 13]. Higher octane ratings generally improve knock resistance, potentially enabling more favorable ignition phasing and more complete combustion.

Ethanol, a renewable biofuel derived from biomass fermentation, possesses an octane number of approximately 111 and contains around 35% oxygen by mass [14-16]. These physicochemical properties influence laminar flame speed, ignition delay, and oxidation kinetics in spark-ignition engines [17]. Besides fuel modification, emission reduction strategies also include optimized engine calibration approaches and combustion control techniques. Previous studies have shown that these strategies improve combustion stability while reducing CO and HC emissions and maintaining overall engine performance under gasoline-ethanol operating conditions [18, 19]. From a combustion chemistry perspective, complete combustion ideally converts fuel into carbon dioxide (CO₂) and water vapor (H₂O), whereas incomplete combustion produces CO and unburned HC [20]. Engine calibration and combustion phasing influence mixture preparation and combustion completeness, particularly for gasoline-ethanol blends [21]. Elevated HC emissions are generally associated with flame quenching, wall wetting, and incomplete oxidation, whereas increased CO concentrations indicate locally rich mixtures where oxygen availability is insufficient for complete carbon oxidation to CO₂ [22, 23]. Consequently, exhaust emission formation is governed by the interaction among fuel chemistry, mixture preparation, combustion temperature, and ignition phasing. Despite extensive investigations of gasohol blends under part-load and performance-oriented operating conditions [9, 10], comparatively limited attention has been devoted to steady idle operation. Under idle conditions, low turbulence intensity, reduced combustion temperature, and mixture stratification increase the likelihood of incomplete combustion. Furthermore, previous studies have generally evaluated either fuel composition or ECU calibration independently rather than systematically investigating their combined interaction under idle emission compliance conditions.

Therefore, this study evaluates the combined effects of fuel octane rating (RON 90, RON 92, and RON 98), gasohol blending ratios (E10 and E40), ignition timing, and fuel injection timing on idle combustion stoichiometry and exhaust emissions. A full-factorial experimental design was employed to identify fuel-calibration combinations associated with compliance with the adopted idle CO and HC emission limits under the investigated idle operating conditions.

2. METHOD

This study employed a full-factorial experimental design to systematically investigate the effects of fuel properties and combustion phasing on idle exhaust emissions under controlled laboratory conditions. Four independent variables were evaluated: fuel grade (RON 90, RON 92, and RON 98), gasohol blending ratio (E10 and E40), ignition timing (3° and 7° before top dead centre (BTDC)), and fuel injection timing (350° and 355° after top dead centre (ATDC)). The 3 × 2 × 2 × 2 factorial designs generated 24 treatment combinations, supplemented by three baseline conditions using the standard

ECU settings for each fuel grade, resulting in a total of 27 operating conditions. This experimental configuration enabled systematic evaluation of the individual and combined effects of the investigated variables while maintaining identical operating conditions for all experimental runs. Detailed engine specifications, fuel specifications, blend properties, estimated octane numbers, and the factorial design matrix are presented in Tables 1-7 to provide a comprehensive description of the experimental setup.

Table 1. Engine specifications

Specification	
Engine type	Four-stroke, Single Overhead Camshaft (SOHC) with air cooling, ESP
Stroke volume	108.2 cc
Fuel supply system	Injection (PGM-FI)
Compression ratio	9.5:1
Maximum power	6.38 kW (8.68 PS)/7,500 rpm
Maximum torque	9.01 N·m (0.92 kgf·m)/6,500 rpm
Starter type	ACG starter, pedal & electric

Table 2. Properties of gasoline and ethanol

Properties	Gasoline	Ethanol
RON	Various	106–115
Representative chemical formula	C ₈ H ₁₈	C ₂ H ₅ OH
Purity (%)	N/A	99.5
Density (20 °C) [kg/m ³]	740–760	789
Viscosity (20 °C) [cSt]	0.64	1.52
Oxygen content (wt.%)	0	34.73
Surface tension (mN/m)	21.58	22.66
Latent heat of vaporization [kJ/kg]	289	854
Stoichiometric air-fuel ratio (AFR) [kg/kg]	14.7	—

Note: RON = Research Octane Number.

Table 3. Estimated octane numbers of E10 and E40 blends prepared from RON 90, RON 92, and RON 98 gasoline

Blend	Ethanol vol. %	Base RON	NOI Value	Blend RON	RON Increase
E10	10	90	26.529	94.51	+4.51
E10	10	92	26.529	95.98	+3.98
E10	10	98	26.529	100.39	+2.39
E40	40	90	82.320	103.99	+13.99
E40	40	92	82.320	104.35	+12.35
E40	40	98	82.320	105.41	+7.41

Note: RON = Research Octane Number.

Table 4. Experimental factors and levels

Code	Factor	1	2	3
A	Fuel Grade	RON 90	RON 92	RON 98
B	Ignition Timing	3° BTDC	7° BTDC	—
C	Injection Timing	355° ATDC	350° ATDC	—
D	Ethanol Blend	E10	E40	—

Note: ATDC = After Top Dead Centre; BTDC = Before Top Dead Centre.

Table 5. Baseline operating conditions (3 samples)

Order	Fuel Grade (A)	Ignition Timing (B)	Injection Timing (C)	Ethanol Blend (D)
1	RON 90	STD	STD	E0
2	RON 92	STD	STD	E0
3	RON 98	STD	STD	E0

Note: RON = Research Octane Number.

Table 6. Factorial treatment combinations (24 samples)

Order	Fuel Grade (A)	Ignition Timing (B)	Injection Timing (C)	Ethanol Blend (D)
RON 90 (No. 4-11 = 8 Samples)				
4	RON 90	3° BTDC	355° ATDC	E10
5	RON 90	7° BTDC	355° ATDC	E10
6	RON 90	3° BTDC	350° ATDC	E10
7	RON 90	7° BTDC	350° ATDC	E10
8	RON 90	3° BTDC	355° ATDC	E40
9	RON 90	7° BTDC	355° ATDC	E40
10	RON 90	3° BTDC	350° ATDC	E40
11	RON 90	7° BTDC	350° ATDC	E40
RON 92 (No. 12-19 = 8 Samples)				
12	RON 92	3° BTDC	355° ATDC	E10
13	RON 92	7° BTDC	355° ATDC	E10
14	RON 92	3° BTDC	350° ATDC	E10
15	RON 92	7° BTDC	350° ATDC	E10
16	RON 92	3° BTDC	355° ATDC	E40
17	RON 92	7° BTDC	355° ATDC	E40
18	RON 92	3° BTDC	350° ATDC	E40
19	RON 92	7° BTDC	350° ATDC	E40
RON 98 (No. 20-27 = 8 Samples)				
20	RON 98	3° BTDC	355° ATDC	E10
21	RON 98	7° BTDC	355° ATDC	E10
22	RON 98	3° BTDC	350° ATDC	E10
23	RON 98	7° BTDC	350° ATDC	E10
24	RON 98	3° BTDC	355° ATDC	E40
25	RON 98	7° BTDC	355° ATDC	E40
26	RON 98	3° BTDC	350° ATDC	E40
27	RON 98	7° BTDC	350° ATDC	E40

Note: RON = Research Octane Number; BTDC = Before Top Dead Centre; ATDC = After Top Dead Centre.

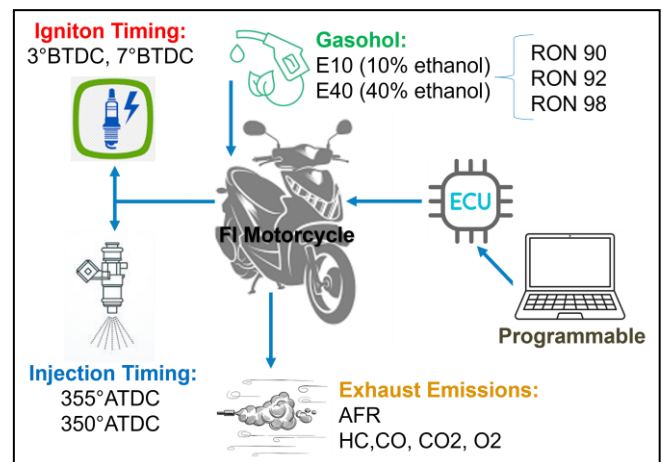
Table 7. Summary of the experimental design

Item	Count
Baseline conditions	3
Treatment conditions	24
Total samples	27
Design type	3 × 2 × 2 × 2 full-factorial design
Factor A levels	3
Factor B levels	2
Factor C levels	2
Factor D levels	2

The experiments were conducted using a production fuel-injected (FI) spark-ignition motorcycle equipped with a programmable ECU, adjustable ignition timing (3° and 7° BTDC), adjustable fuel injection timing (350° and 355° ATDC), and a real-time exhaust gas analyzer. All tests were performed at a stabilized idle speed of approximately 1200 rpm under steady operating conditions. Each operating condition was measured three consecutive times, and the reported AFR, CO, HC, CO₂, and O₂ values represent the arithmetic mean of the three measurements. The repeated measurements were performed to improve the consistency of the recorded emission data under identical test conditions. Standard deviations were not included because the objective of the study was to compare emission characteristics among the investigated operating conditions rather than to perform statistical inference. The overall experimental design is illustrated in Figure 1.

In Figure 1, A 3 × 2 × 2 × 2 full-factorial design generated 24 E10/E40 treatment combinations, supplemented by three E0 baseline conditions, resulting in 27 operating conditions. The investigated factors comprised three gasoline grades (RON 90, RON 92, and RON 98), two ignition timings (3° and 7° BTDC), and two fuel injection timings (350° and 355° ATDC). Exhaust emissions (CO, HC, CO₂, and O₂) together

with AFR were measured under steady idle operating conditions.

**Figure 1.** Experimental design adopted in this study

Gasohol blends (E10 and E40) were prepared volumetrically by mixing commercially available RON 90, RON 92, and RON 98 gasoline with anhydrous ethanol according to the predetermined blending ratios. Ignition timing and fuel injection timing were adjusted according to the predefined factorial matrix for each operating condition. Exhaust emissions were measured using a calibrated gas analyzer equipped with non-dispersive infrared (NDIR) sensors for CO and CO₂ and a flame ionization detector (FID) for HC. AFR was monitored using a wideband oxygen sensor. Instrument calibration was performed before each measurement sequence using certified zero and span gases to ensure measurement reliability.

Ignition timing and fuel injection timing were selected

based on previous studies demonstrating their influence on combustion stability and exhaust emissions in fuel-injected spark-ignition engines [1, 3, 22, 24]. All remaining engine parameters were kept constant to isolate the effects of fuel composition and combustion phasing. The emission thresholds adopted in this study correspond to the idle CO and HC limits specified in the Indonesian Ministry of Environment and Forestry Regulation (PERMEN LHK No. 5 Tahun 2023). These limits were used solely as idle emission evaluation criteria and should not be interpreted as full Euro 4 type-approval certification.

Experimental results were classified as fully compliant, partially compliant, or non-compliant according to the adopted idle CO and HC emission limits. Stoichiometric analysis was performed to examine relationships among AFR, CO, HC, CO₂, and residual O₂, while the most favorable and least favorable operating conditions were compared to evaluate the combined effects of fuel properties and ECU calibration.

3. RESULTS

3.1 Combustion stoichiometry

For clarity, the stoichiometric calculations presented in this section employ representative surrogate hydrocarbon compounds to illustrate the influence of ethanol blending on theoretical combustion behavior. Commercial gasoline is a complex mixture of numerous hydrocarbons; therefore, the molecular formulas assigned to RON 90, RON 92, and RON 98 are intended solely as representative surrogate compounds for illustrative stoichiometric calculations and should not be interpreted as the actual chemical compositions of commercial gasoline fuels.

Based on these representative surrogate formulations, the stoichiometric analysis presented in Table 8 illustrates how increasing ethanol content influences the elemental composition of the fuel blends. The surrogate gasoline compounds contain only carbon and hydrogen atoms, whereas ethanol (C₂H₅OH) contributes chemically bound oxygen atoms. Consequently, increasing the ethanol blending ratio progressively increases the oxygen content of the representative fuel composition.

Using these surrogate formulations, the theoretical stoichiometric oxygen demand was calculated, as summarized in Table 9. The calculations indicate that surrogate hydrocarbon with higher carbon numbers require greater theoretical oxygen demand for complete combustion, whereas ethanol requires comparatively less external oxygen because part of the required oxygen is already contained within its molecular structure. Accordingly, the representative E10 and E40 surrogate blends exhibit corresponding changes in theoretical oxygen demand and combustion products.

The combustion equations, oxygen requirements, and theoretical AFR presented in Tables 8-10 are intended solely as representative stoichiometric calculations for comparative analysis and do not represent the exact combustion chemistry or molecular composition of commercial RON 90, RON 92, and RON 98 gasolines, whose compositions vary with refinery processes and formulations. Nevertheless, these calculations provide a framework for interpreting experimental emission results by illustrating how fuel composition influences theoretical oxygen demand, combustion products, and AFR.

Finally, Table 10 summarizes the theoretical combustion

stoichiometry and corresponding AFR values derived from the representative surrogate formulations. The representative gasoline surrogates require approximately 15.0-15.3 AFR for complete combustion, whereas ethanol requires approximately 9.0 AFR because of its chemically bound oxygen. Consequently, the representative E10 blends exhibit theoretical AFR values ranging from 14.8 to 15.2, while the representative E40 blends range from 13.8 to 14.3. These theoretical AFR values are consistent with the reduced external oxygen demand as ethanol content increases.

Table 8. Representative surrogate fuel composition used for stoichiometric illustration

Fuel	Formula	Atom		
		C	H	O
RON 90	C ₉ H ₂₀	9	20	0
RON 92	C ₁₀ H ₂₄	10	24	0
RON 98	C ₁₁ H ₂₄	11	24	0
Ethanol	C ₂ H ₅ OH	2	6	1
E10 (RON 90)	9C ₉ H ₂₀ + C ₂ H ₅ OH	83	186	1
E10 (RON 92)	9C ₁₀ H ₂₄ + C ₂ H ₅ OH	92	222	1
E10 (P. Turbo)	9C ₁₁ H ₂₄ + C ₂ H ₅ OH	101	222	1
E40 (RON 90)	3C ₉ H ₂₀ + 2C ₂ H ₅ OH	31	72	2
E40 (RON 92)	3C ₁₀ H ₂₄ + 2C ₂ H ₅ OH	34	84	2
E40 (RON 98)	3C ₁₁ H ₂₄ + 2C ₂ H ₅ OH	37	84	2

Note: RON = Research Octane Number.

Table 9. Theoretical stoichiometric oxygen requirements and combustion products calculated using a representative surrogate hydrocarbon

Fuel	Formula		
RON 90	C ₉ H ₂₀ + 14(O ₂ + 3.76N ₂)		
RON 92	C ₁₀ H ₂₄ + 16(O ₂ + 3.76N ₂)		
RON 98	C ₁₁ H ₂₄ + 17(O ₂ + 3.76N ₂)		
Ethanol	C ₂ H ₅ OH + 3(O ₂ + 3.76N ₂)		
E10 (RON 90)	9C ₉ H ₂₀ + C ₂ H ₅ OH + 129(O ₂ + 3.76N ₂)		
E10 (RON 92)	9C ₁₀ H ₂₄ + C ₂ H ₅ OH + 147(O ₂ + 3.76N ₂)		
E10 (RON 98)	9C ₁₁ H ₂₄ + C ₂ H ₅ OH + 156(O ₂ + 3.76N ₂)		
E40 (RON 90)	3C ₉ H ₂₀ + 2C ₂ H ₅ OH + 48(O ₂ + 3.76N ₂)		
E40 (RON 92)	3C ₁₀ H ₂₄ + 2C ₂ H ₅ OH + 54(O ₂ + 3.76N ₂)		
E40 (RON 98)	3C ₁₁ H ₂₄ + 2C ₂ H ₅ OH + 57(O ₂ + 3.76N ₂)		

Fuel	Mass (g)		
	Fuel	O ₂	N ₂
RON 90	128	448	1,473.92
RON 92	144	512	1,684.48
RON 98	156	544	1,789.76
Ethanol	46	96	315.84
E10 (RON 90)	1,198	4,128	13,581.12
E10 (RON 92)	1,342	4,704	15,476.16
E10 (RON 98)	1,450	4,992	16,423.68
E40 (RON 90)	476	1,536	5,053.44
E40 (RON 92)	524	1,728	5,685.12
E40 (RON 98)	560	1,824	6,000.96

Fuel	Mol			
	O ₂	N ₂	CO ₂	H ₂ O
RON 90	14	52.64	9	10
RON 92	16	60.16	10	12
RON 98	17	63.92	11	12
Ethanol	3	11.28	2	3
E10 (RON 90)	129	485.04	83	93
E10 (RON 92)	147	552.72	92	111
E10 (RON 98)	156	586.56	101	111
E40 (RON 90)	48	180.48	31	36
E40 (RON 92)	54	203.04	34	42
E40 (RON 98)	57	214.32	37	42

Note: RON = Research Octane Number; CO = Carbon Monoxide; HC = Hydrocarbon; CO₂ = Carbon Dioxide; O₂ = Oxygen; N₂ = Nitrogen.

Although actual engine operation is influenced by factors such as fuel atomization, in-cylinder mixture formation, ignition timing, fuel injection timing, and ECU control strategies, the stoichiometric calculations provide a useful theoretical reference for interpreting the experimental trends observed in AFR and exhaust emissions under the investigated

idle operating conditions. The progressive reduction in theoretical AFR with increasing ethanol content therefore reflects the lower theoretical air requirement for complete combustion and provides a scientific basis for interpreting the combustion characteristics and emission behavior discussed in the following sections.

Table 10. Representative combustion stoichiometry and theoretical air-fuel ratio (AFR)

Fuel	Combustion Stoichiometry	AFR
RON 90	$C_9H_{20} + 14(O_2 + 3.76N_2) \rightarrow 9CO_2 + 10H_2O + 52.64N_2$	15.0:1
RON 92	$C_{10}H_{24} + 16(O_2 + 3.76N_2) \rightarrow 10CO_2 + 12H_2O + 60.16N_2$	15.3:1
RON 98	$C_{11}H_{24} + 17(O_2 + 3.76N_2) \rightarrow 11CO_2 + 12H_2O + 63.92N_2$	15.0:1
Ethanol	$C_2H_5OH + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 11.28N_2$	9.0:1
E10 (RON 90)	$9C_9H_{20} + C_2H_5OH + 129(O_2 + 3.76N_2) \rightarrow 83CO_2 + 93H_2O + 485.04N_2$	14.8:1
E10 (RON 92)	$9C_{10}H_{24} + C_2H_5OH + 147(O_2 + 3.76N_2) \rightarrow 92CO_2 + 111H_2O + 552.72N_2$	15.2:1
E10 (RON 98)	$9C_{11}H_{24} + C_2H_5OH + 156(O_2 + 3.76N_2) \rightarrow 101CO_2 + 111H_2O + 586.56N_2$	14.8:1
E40 (RON 90)	$3C_9H_{20} + 2C_2H_5OH + 48(O_2 + 3.76N_2) \rightarrow 31CO_2 + 36H_2O + 180.48N_2$	13.8:1
E40 (RON 92)	$3C_{10}H_{24} + 2C_2H_5OH + 54(O_2 + 3.76N_2) \rightarrow 34CO_2 + 42H_2O + 203.04N_2$	14.3:1
E40 (RON 98)	$3C_{11}H_{24} + 2C_2H_5OH + 57(O_2 + 3.76N_2) \rightarrow 37CO_2 + 42H_2O + 214.32N_2$	14.0:1

Note: RON = Research Octane Number.

3.2 Hydrocarbon emissions

As illustrated in Figure 2, HC emissions ranged from 200.7 to 1,337.7 ppm across the 27 idle operating conditions. Based on the adopted idle HC emission limit of 1,000 ppm, 22 operating conditions (81.5%) complied with the criterion, whereas the remaining five conditions (18.5%) exceeded the limit. The exceedances occurred in Orders 5, 6, 7, 16, and 17, indicating that excessive HC emissions were confined to a limited number of operating conditions. Among the 24 factorial treatment conditions, the lowest HC emission was obtained with Gasohol E40 (RON 98) at an ignition timing of 3° BTDC and a fuel injection timing of 350° ATDC (Order 26), producing 318.7 ppm. In contrast, the highest HC emission was recorded for Gasohol E10 (RON 90) at 7° BTDC and 355° ATDC (Order 5), reaching 1,337.7 ppm.

emissions, with three of the four operating conditions exceeding the adopted limit (Orders 5–7). For the E40 blends, RON 90 remained fully compliant under all operating conditions, with HC emissions ranging from 375.0 to 711.3 ppm. RON 92 exhibited the least favorable HC performance within the E40 group, producing HC emissions between 544.3 and 1054.0 ppm, with two operating conditions (Orders 16 and 17) exceeding the adopted limit. RON 98 maintained satisfactory HC performance, with emissions ranging from 304.0 to 579.3 ppm across all four timing combinations.

The experimental results further indicate that the combination of 7° BTDC ignition timing and 355° ATDC fuel injection timing generally resulted in higher HC emissions, particularly for lower-octane fuels. Conversely, advancing the fuel injection timing to 350° ATDC generally reduced HC emissions under comparable operating conditions, suggesting improved combustion completeness. Overall, the results demonstrate that compliance with the adopted idle HC emission limit depends on an appropriate combination of fuel octane rating, ethanol blending ratio, and coordinated ignition and fuel injection timing under idle operating conditions.

3.3 Carbon monoxide emissions

As illustrated in Figure 3, 11 of the 27 idle operating conditions (40.7%) satisfied the adopted idle CO emission limit of 3.0 vol.%, whereas the remaining 16 conditions (59.3%) exceeded the limit. Compared with HC emissions, CO control represented the more restrictive requirement for achieving overall idle emission compliance. Among the 24 factorial treatment conditions, the lowest CO emission was obtained with Gasohol E40 (RON 98) at an ignition timing of 3° BTDC and a fuel injection timing of 350° ATDC (Order 26), producing 0.57 vol.%. In contrast, the highest CO emission was recorded for Gasohol E40 (RON 92) at 7° BTDC and 355° ATDC (Order 17), reaching 7.42 vol.%. For the E10 blends, RON 92 consistently complied with the adopted idle CO emission limit under all four timing combinations, with CO emissions ranging from 1.45 to 2.24 vol.%. In contrast, RON 90 exhibited substantially higher CO emissions, ranging from 4.50 to 7.27 vol.%, and none of the four operating conditions satisfied the adopted limit. RON 98 showed intermediate performance, with CO emissions ranging

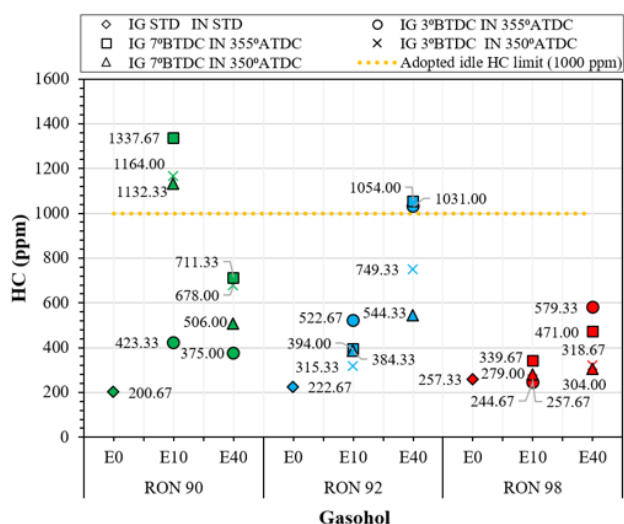


Figure 2. Hydrocarbon (HC) emissions under the 27 investigated idle operating conditions

For the E10 blends, RON 92 and RON 98 satisfied the adopted idle HC emission limit under all four timing combinations. HC emissions ranged from 315.3 to 522.7 ppm for RON 92 and from 244.7 to 339.7 ppm for RON 98. In contrast, RON 90 exhibited substantially higher HC

from 2.23 to 4.43 vol.%, where two of the four operating conditions achieved compliance.

For the E40 blends, RON 98 produced the lowest overall CO emissions, ranging from 0.57 to 5.34 vol.%, with two operating conditions (Orders 26 and 27) satisfying the adopted idle CO emission limit. RON 90 exhibited CO emissions between 1.87 and 5.44 vol.%, with one compliant operating condition (Order 15). In comparison, RON 92 produced CO emissions ranging from 3.93 to 7.42 vol.%, and none of the operating conditions complied with the adopted limit. Across all fuel grades, advancing the fuel injection timing to 350° ATDC generally reduced CO emissions relative to the corresponding 355° ATDC setting, indicating improved combustion efficiency under idle operation. Overall, the results demonstrate that compliance with the adopted idle CO emission limit depends on the combined effects of fuel octane rating, ethanol blending ratio, and coordinated ignition and fuel injection timing.

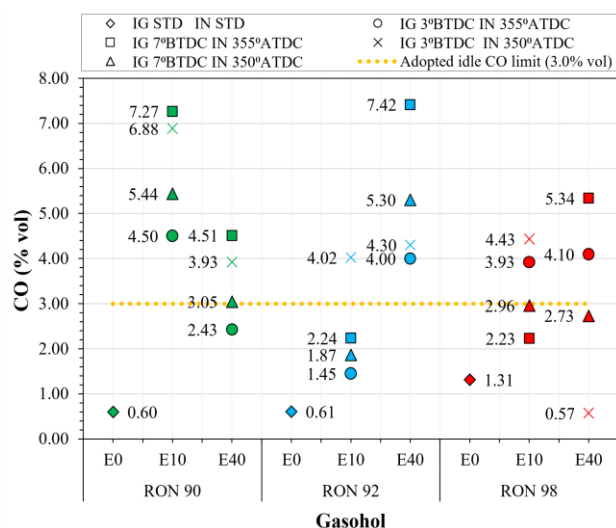


Figure 3. Carbon monoxide (CO) emissions under the 27 investigated idle operating conditions

3.4 Carbon dioxide emissions

As illustrated in Figure 4, CO₂ concentrations at idle ranged from 4.7 to 12.6 vol.%, indicating considerable variation in combustion characteristics among the investigated operating conditions. Among the 24 factorial treatment conditions, the highest CO₂ concentration was obtained with Gasohol E40 (RON 98) at an ignition timing of 3° BTDC and a fuel injection timing of 350° ATDC (Order 26), producing 12.4 vol.%. In contrast, the lowest CO₂ concentration was observed for the same fuel at 3° BTDC and 355° ATDC (Order 24), with only 4.7 vol.%. These results demonstrate that combustion characteristics were influenced by the combined effects of fuel properties and ignition–injection timing.

Higher CO₂ concentrations were generally associated with lower CO and HC emissions, suggesting more complete combustion under idle operating conditions. Most operating conditions with CO₂ concentrations above approximately 11.6 vol.% satisfied the adopted idle CO and HC emission limits, whereas lower CO₂ concentrations were frequently accompanied by increased CO and HC emissions. For the E10 blends, RON 92 maintained relatively stable CO₂ concentrations between 10.8 and 11.7 vol.% across all timing combinations, corresponding to consistently low HC

emissions and full compliance with the adopted idle HC emission limit. In contrast, RON 90 exhibited lower CO₂ concentrations, reaching a minimum of 7.8 vol.%, which coincided with the highest HC emission recorded in the present study.

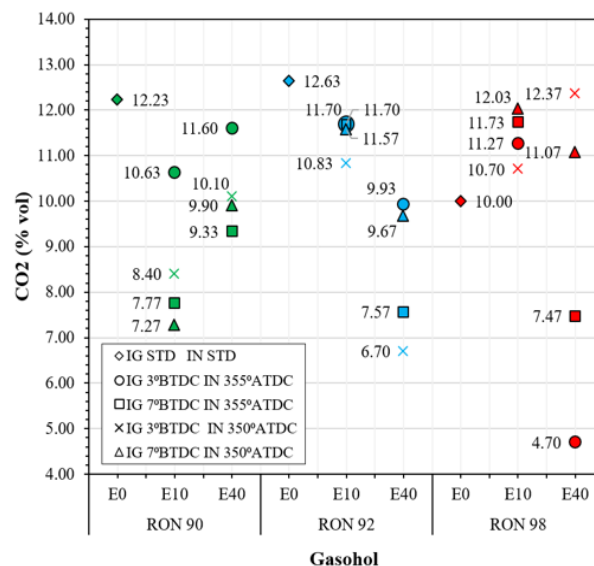


Figure 4. Carbon dioxide (CO₂) concentrations under the 27 investigated idle operating conditions

The E40 blends exhibited greater variation in CO₂ concentration than the E10 blends. CO₂ concentrations ranged from 7.3 to 11.6 vol.% for RON 90, from 6.7 to 11.7 vol.% for RON 92, and from 4.7 to 12.4 vol.% for RON 98. Across all fuel grades, advancing the fuel injection timing to 350° ATDC generally increased CO₂ concentrations relative to the corresponding 355° ATDC setting, indicating improved combustion completeness. Overall, the results suggest that CO₂ concentration is a useful indicator of combustion quality and is generally associated with improved idle emission performance under the investigated operating conditions.

3.5 Residual oxygen emissions

As illustrated in Figure 5, residual O₂ concentrations at idle ranged from 0.46 to 9.31 vol.%, indicating substantial variation in oxygen utilization among the investigated operating conditions. Among the 24 factorial treatment conditions, the lowest residual O₂ concentration was obtained with Gasohol E10 (RON 92) at an ignition timing of 3° BTDC and a fuel injection timing of 350° ATDC (Order 14), producing 0.46 vol.%. In contrast, the highest residual O₂ concentration was observed for Gasohol E40 (RON 98) at 3° BTDC and 355° ATDC (Order 24), reaching 9.31 vol.%.

Most operating conditions that satisfied the adopted idle CO and HC emission limits exhibited residual O₂ concentrations between approximately 0.7 and 1.8 vol.%, although one compliant lean-burn condition showed a higher O₂ concentration. For the E10 blends, RON 92 maintained relatively stable residual O₂ concentrations ranging from 0.46 to 1.65 vol.% across all timing combinations, corresponding to consistently low CO and HC emissions. In contrast, RON 90 exhibited a wider O₂ range (0.71–4.27 vol.%), with the highest value occurring at 7° BTDC and 350° ATDC, where elevated residual oxygen was accompanied by increased HC emissions.

The E40 blends exhibited greater variation in residual O₂ concentration than the E10 blends. Residual O₂ ranged from 1.09 to 4.27 vol.% for RON 90, from 1.73 to 5.89 vol.% for RON 92, and from 0.66 to 9.31 vol.% for RON 98. Across all fuel grades, advancing the fuel injection timing to 350° ATDC generally reduced residual O₂ relative to the corresponding 355° ATDC setting, suggesting more effective oxygen utilization during combustion. Overall, the results indicate that residual O₂ is a useful indicator of combustion quality and, when interpreted together with AFR, CO₂, CO, and HC, provides additional insight into combustion completeness under idle operating conditions.

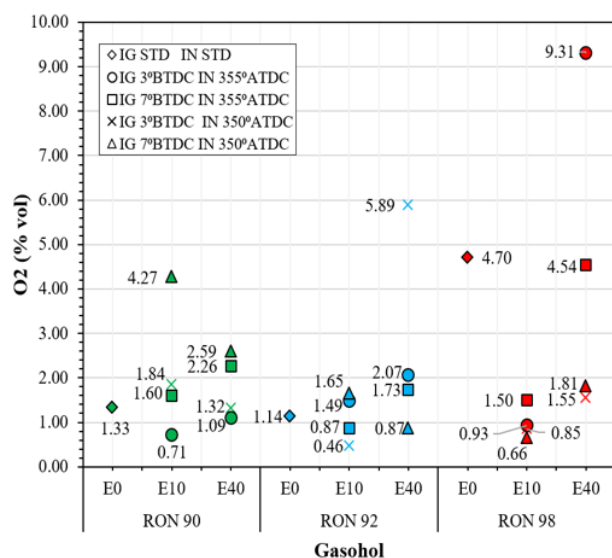


Figure 5. Residual oxygen (O₂) concentrations under the 27 investigated idle operating conditions

3.6 Air-fuel ratio

As illustrated in Figure 6, AFR values ranged from 11.7 to 21.2 across the 27 idle operating conditions, indicating substantial variation in mixture preparation under different fuel blends and ECU timing settings. For reference, the stoichiometric AFR of conventional gasoline is approximately 14.7:1. Gasohol E10 (RON 92) generally maintained AFR values between 14.0 and 14.7, corresponding to comparatively lower CO and HC emissions. In contrast, Gasohol E10 (RON 90) exhibited a wider AFR range (11.7–14.3), accompanied by higher CO and HC emissions under several operating conditions.

The highest AFR (21.2) was observed for Gasohol E40 (RON 98) at an ignition timing of 3° BTDC and a fuel injection timing of 355° ATDC (Order 24). This operating condition was accompanied by 9.31 vol.% O₂, 4.7 vol.% CO₂, and 4.10 vol.% CO, suggesting that combustion deviated substantially from the conditions associated with lower emissions. However, the underlying cause could not be established because no additional combustion diagnostic measurements were performed.

Most operating conditions that satisfied the adopted idle CO and HC emission limits were clustered around AFR values between approximately 14.0 and 15.5. In comparison, the E40 blends exhibited a wider AFR distribution than the E10 blends. AFR values ranged from 13.0 to 14.7 for Gasohol E40 (RON 90), from 11.8 to 16.7 for Gasohol E40 (RON 92), and from 12.5 to 21.2 for Gasohol E40 (RON 98). Advancing the fuel

injection timing to 350° ATDC generally produced a narrower AFR distribution than the corresponding 355° ATDC setting under the investigated operating conditions.

Overall, operating conditions with AFR values closer to the stoichiometric range generally exhibited lower exhaust emissions under idle operation. Nevertheless, AFR alone was insufficient to explain emission behavior, indicating that fuel properties, ethanol blending ratio, and coordinated ignition and fuel injection timing also contributed to the observed combustion characteristics.

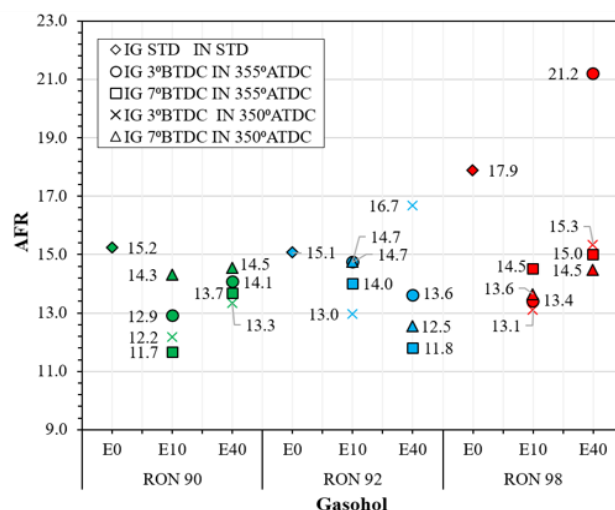


Figure 6. Air-fuel ratio (AFR) under the 27 investigated idle operating conditions

3.7 Emission compliance status by experimental order

To facilitate comparison of the emission results presented in the preceding sections, Table 11 provides a comprehensive summary of the 27 experimental operating conditions. The table compiles the measured AFR, CO, HC, CO₂, and residual O₂ concentrations together with the corresponding compliance status based on the adopted idle CO (<3.0 vol.%) and HC (<1,000 ppm) emission limits.

As shown in Table 11, 11 operating conditions satisfied both the adopted idle CO and HC emission limits, 11 conditions satisfied only one of the two criteria, and the remaining five operating conditions exceeded both limits. This consolidated presentation provides a comprehensive overview of the experimental dataset and facilitates direct comparison among all investigated operating conditions.

Within the present experimental dataset, the operating conditions that satisfied both emission limits generally exhibited AFR values between approximately 14.0 and 15.5, accompanied by CO₂ concentrations above approximately 11.6 vol.% and residual O₂ concentrations below approximately 1.8 vol.%. These observations indicate that compliant operating conditions tended to cluster within these ranges under the investigated idle operating conditions. Nevertheless, these values represent empirical trends observed in the present study and should not be interpreted as universal combustion criteria.

The operating conditions classified as partial compliance generally satisfied either the CO or HC emission limit but not both simultaneously. In most cases, HC emissions remained below the adopted limit, whereas CO concentrations exceeded the allowable threshold, indicating that CO control represented the more restrictive requirement for achieving overall idle

emission compliance. This behavior suggests that the evaluated fuel blends and ECU calibration settings influenced combustion characteristics differently under idle operation.

Five operating conditions were classified as non-compliant, exceeding both the adopted idle CO and HC emission limits. These operating conditions were generally associated with either relatively rich combustion or markedly lean operating conditions. For example, Operating Condition 24 exhibited an AFR of 21.2, residual O₂ of 9.31 vol.%, CO₂ of 4.7 vol.%, and CO of 4.10 vol.%. This emission pattern differed substantially from that observed for the compliant operating conditions. However, because no additional combustion diagnostic measurements were performed, the underlying cause could not be established, and no definitive conclusion regarding the combustion mechanism can be drawn from the present results.

Overall, Table 11 provides a unified presentation of the complete emission dataset and supports the consistency of the interpretations presented in the preceding sections. Within the scope of the present idle experiments, the results suggest that compliance with the adopted idle CO and HC emission limits was associated with appropriate combinations of fuel properties, ethanol blending ratio, ignition timing, fuel injection timing, and combustion conditions approaching the stoichiometric AFR. Further investigations under broader

engine operating conditions are required before these observations can be generalized beyond the present experimental conditions.

3.8 E10 compliance

The compliance performance of the E10 fuel blends varied according to fuel grade and ECU calibration, as summarized in Table 12. Of the twelve E10 operating conditions evaluated, five satisfied both the adopted idle CO and HC emission limits. Among the three fuel grades, Gasohol E10 (RON 92) demonstrated the highest level of compliance, with all four timing combinations meeting both emission criteria. CO emissions ranged from 1.45 to 2.24 vol.%, while HC emissions ranged from 394.0 to 522.7 ppm, indicating consistently stable emission performance under the investigated idle conditions.

In contrast, none of the four Gasohol E10 (RON 90) operating conditions satisfied both emission limits simultaneously. Elevated CO emissions were observed under all timing combinations, while HC concentrations exceeded the adopted limit under three operating conditions (Orders 5–7). The highest emissions occurred at 7° BTDC ignition timing and 355° ATDC injection timing, where CO reached 7.27 vol.% and HC reached 1,337.7 ppm.

Table 11. Summary of idle emission characteristics and compliance status

Order	AFR	CO (vol.%)	HC (ppm)	CO ₂ (vol.%)	O ₂ (vol.%)	Status of Compliance
1	15.2	0.60	200.7	12.2	1.33	Full
2	15.1	0.61	222.7	12.6	1.14	Full
3	17.9	1.31	257.3	10.0	4.70	Full
4	12.9	4.50	423.3	10.6	0.71	Partial
5	11.7	7.27	1,337.7	7.8	1.60	None
6	12.2	6.88	1,164.0	8.4	1.84	None
7	14.3	5.44	1,132.3	7.3	4.27	None
8	14.1	2.43	375.0	11.6	1.09	Full
9	13.7	4.51	711.3	9.3	2.26	Partial
10	13.3	3.93	678.0	10.1	1.32	Partial
11	14.5	3.05	506.0	9.9	2.59	Partial
12	14.7	1.45	522.7	11.7	1.49	Full
13	14.0	2.24	394.0	11.7	0.87	Full
14	13.0	4.02	315.3	10.8	0.46	Partial
15	14.7	1.87	384.3	11.6	1.65	Full
16	13.6	4.00	1,031.0	9.9	2.07	None
17	11.8	7.42	1,054.0	7.6	1.73	None
18	16.7	4.30	749.3	6.7	5.89	Partial
19	12.5	5.30	544.3	9.7	0.87	Partial
20	13.4	3.93	244.7	11.3	0.93	Partial
21	14.5	2.23	339.7	11.7	1.50	Full
22	13.1	4.43	257.7	10.7	0.85	Partial
23	13.6	2.96	279.0	12.0	0.66	Full
24	21.2	4.10	579.3	4.7	9.31	Partial
25	15.0	5.34	471.0	7.5	4.54	Partial
26	15.3	0.57	318.7	12.4	1.55	Full
27	14.5	2.73	304.0	11.1	1.81	Full

Note: AFR = Air–Fuel Ratio; CO = Carbon Monoxide; HC = Hydrocarbon; CO₂ = Carbon Dioxide; O₂ = Oxygen.

Table 12. Fully compliant E10 operating conditions

Order	Fuel Grade	Operating Condition	CO (vol.%)	HC (ppm)	Compliance margin
12	RON 92	3° BTDC + 355° ATDC	1.45	522.7	CO +1.55, HC + 477.3
13	RON 92	7° BTDC + 355° ATDC	2.24	394.0	CO +0.76, HC + 606.0
15	RON 92	7° BTDC + 350° ATDC	1.87	384.3	CO +1.13, HC + 615.7
21	RON 98	7° BTDC + 355° ATDC	2.23	339.7	CO +0.77, HC + 660.3
23	RON 98	7° BTDC + 350° ATDC	2.96	279.0	CO +0.04, HC + 721.0

Note: RON = Research Octane Number; BTDC = Before Top Dead Centre; ATDC = After Top Dead Centre; CO = Carbon Monoxide; HC = Hydrocarbon.

Gasohol E10 (RON 98) achieved compliance in two of the four operating conditions. The compliant conditions were obtained using 7° BTDC ignition timing, whereas both operating conditions with 3° BTDC ignition timing exceeded the adopted CO emission limit despite maintaining HC concentrations below 1,000 ppm. These results indicate that the emission performance of the investigated E10 blends depended on the combined effects of fuel grade and ignition–injection timing under idle operation.

3.9 E40 compliance

The emission performance of the E40 fuel blends also depended on fuel grade and ECU calibration, as summarized in Table 13. Among the twelve E40 operating conditions, three satisfied both the adopted idle CO and HC emission limits.

Gasohol E40 (RON 98) exhibited the highest compliance among the E40 blends, with two of the four operating conditions satisfying both emission criteria. The lowest emissions were obtained at 3° BTDC ignition timing and 350° ATDC injection timing, producing 0.57 vol.% CO and 318.7 ppm HC. In contrast, the operating condition using 3° BTDC ignition timing and 355° ATDC injection timing exhibited an AFR of 21.2, residual O₂ of 9.31 vol.%, CO₂ of 4.7 vol.%, and CO of 4.10 vol.%, differing substantially from the emission characteristics observed under the compliant operating conditions.

None of the four Gasohol E40 (RON 92) operating conditions satisfied both adopted idle emission limits. Although several operating conditions maintained HC concentrations close to the adopted limit, CO emissions remained above 3.0 vol.% under all investigated timing combinations. The least favorable emission performance occurred at 7° BTDC ignition timing and 355° ATDC injection timing, producing 7.42 vol.% CO and 1054.0 ppm HC.

Gasohol E40 (RON 90) achieved compliance in one of the

four operating conditions. The compliant condition was obtained at 3° BTDC ignition timing and 355° ATDC injection timing, producing 2.43 vol.% CO and 375.0 ppm HC, whereas the remaining operating conditions exceeded either the CO limit or both adopted emission limits. Overall, the results indicate that the emission performance of the investigated E40 blends was strongly influenced by the interaction between fuel grade and ECU timing under idle operating conditions.

3.10 Least favorable operating condition

Among the 27 operating conditions investigated, the least favorable emission performance was observed for Gasohol E10 (RON 90) with 7° BTDC ignition timing and 355° ATDC injection timing, as summarized in Table 14. This operating condition exceeded both the adopted idle CO and HC emission limits, producing 7.27 vol.% CO and 1,337.7 ppm HC.

Compared with the corresponding RON 90 baseline condition, CO increased from 0.60 to 7.27 vol.%, while HC increased from 200.7 to 1,337.7 ppm. In addition, CO₂ decreased to 7.8 vol.% and residual O₂ was measured at 1.60 vol.%, accompanied by an AFR of 11.7. Collectively, these emission characteristics differed substantially from those observed under the compliant operating conditions and were consistent with relatively incomplete combustion under the investigated idle condition.

The observed emission pattern suggests that the combination of low-octane fuel, E10 blending, and the selected ignition and injection timing was less favorable than the other operating conditions evaluated in this study. However, because no in-cylinder combustion diagnostics or knock measurements were performed, the underlying combustion mechanism cannot be determined from the present dataset. These findings indicate that the investigated calibration combination was not suitable for satisfying the adopted idle CO and HC emission limits under the experimental conditions considered.

Table 13. Fully compliant E40 operating conditions

Order	Fuel Grade	Operating Condition	CO (vol.%)	HC (ppm)	Compliance margin
8	RON 90	3° BTDC + 355° ATDC	2.43	375.0	CO + 0.57, HC + 625.0
26	RON 98	3° BTDC + 350° ATDC	0.57	318.7	CO + 2.43, HC + 681.3
27	RON 98	7° BTDC + 350° ATDC	2.73	304.0	CO + 0.27, HC + 696.0

Note: RON = Research Octane Number; BTDC = Before Top Dead Centre; ATDC = After Top Dead Centre; CO = Carbon Monoxide; HC = Hydrocarbon.

Table 14. Emission characteristics of the least favorable operating condition

Parameter	Test Condition (Order 5)	Baseline (Order 1)	Difference	Limit	Status
CO	7.27	0.60	+6.67	<3.0	above limit
HC	1,337.7	200.7	+1,137	<1000	above limit
AFR	11.7	15.1	-3.4	-	rich mixture
CO ₂	7.8	12.6	-4.8	-	reduced combustion efficiency
O ₂	1.60	1.14	+0.46	-	elevated residual O ₂

Note: CO = Carbon Monoxide; HC = Hydrocarbon; AFR = Air–Fuel Ratio; CO₂ = Carbon Dioxide; O₂ = Oxygen.

Table 15. Emission characteristics of the most favorable operating condition

Parameter	Test Condition (Order 26)	Baseline (Order 3)	Difference	Limit	Status
CO	0.57	1.31	-0.74	<3.0	fully compliant
HC	318.7	257.3	+61.4	<1000	fully compliant
AFR	15.3	17.9	-2.6	-	near stoichiometric
CO ₂	12.4	10.0	+2.4	-	high combustion efficiency
O ₂	1.55	4.70	-3.15	-	low residual oxygen

Note: CO = Carbon Monoxide; HC = Hydrocarbon; AFR = air–fuel ratio; CO₂ = Carbon Dioxide; O₂ = Oxygen.

3.11 Most favorable operating condition

The most favorable emission performance among the investigated operating conditions was obtained using Gasohol E40 (RON 98) with 3° BTDC ignition timing and 350° ATDC injection timing, as summarized in Table 15. This operating condition produced the lowest measured CO concentration (0.57 vol.%) together with an HC concentration of 318.7 ppm, satisfying both adopted idle CO and HC emission limits while providing the largest compliance margin observed in the present study.

Relative to the corresponding RON 98 baseline condition, CO decreased from 1.31 to 0.57 vol.%, whereas HC increased slightly from 257.3 to 318.7 ppm while remaining well below the adopted emission limit. In addition, CO₂ reached 12.4 vol.%, residual O₂ was 1.55 vol.%, and the measured AFR was 15.3, indicating combustion characteristics consistent with those generally associated with compliant operating conditions under idle engine operation. This combination of emission parameters suggests that the selected operating condition promoted relatively efficient combustion while maintaining all measured emissions within the adopted idle limits.

Within the scope of the present investigation, this operating condition exhibited the most favorable combination of AFR and exhaust emission characteristics among the 27 operating conditions evaluated. Overall, the experimental results demonstrate that idle exhaust emissions were strongly influenced by the combined effects of fuel grade, ethanol blending ratio, ignition timing, and fuel injection timing. Of the 27 operating conditions investigated, only 11 satisfied both adopted idle emission limits, highlighting the importance of appropriate fuel selection and ECU calibration for achieving improved emission performance under the investigated idle conditions. These findings further indicate that favorable emission performance depended on the combined optimization of fuel characteristics and engine calibration rather than on any single operating parameter. The implications of these findings and their relationship to combustion behavior are discussed in the following section.

4. DISCUSSION

The present study demonstrates that idle exhaust emissions are influenced by the combined effects of fuel properties and ECU calibration. Among the 27 operating conditions evaluated, only 11 satisfied both the adopted idle CO and HC emission limits, indicating that emission compliance under idle operation depends on the interaction between fuel grade, ethanol blending ratio, ignition timing, and fuel injection timing rather than on a single parameter. Operating conditions that achieved compliance generally exhibited AFR values close to the stoichiometric range together with relatively high CO₂ concentrations and low residual O₂ levels, suggesting more complete combustion under the investigated idle conditions.

4.1 Influence of ethanol fraction and octane rating

Increasing the ethanol blending ratio, particularly to E40, generally improved emission performance when appropriate ignition and injection timing were applied. The oxygen contained within ethanol can promote oxidation during

combustion, while its combustion characteristics differ from those of conventional gasoline, contributing to variations in emission behavior reported in previous studies [17, 21]. In the present investigation, however, the influence of ethanol was strongly dependent on ECU calibration, indicating that increasing ethanol content alone did not consistently reduce emissions.

The experimental results showed that several E10 operating conditions produced lower emissions than comparable E40 conditions, whereas other E40 configurations achieved the lowest overall CO concentrations. These findings suggest that the emission response resulted from the interaction between ethanol blending ratio and combustion calibration rather than from ethanol concentration alone. Similar observations have been reported for gasoline–ethanol-fueled spark-ignition engines, where emission characteristics depend on both fuel properties and engine operating parameters [1, 3, 22].

Fuel octane rating also influenced emission characteristics. Under the investigated idle conditions, RON 98 generally exhibited more favorable emission performance than RON 90, particularly when combined with the 350° ATDC injection timing. The higher resistance to abnormal combustion associated with higher-octane fuels may contribute to more stable combustion under suitable calibration, consistent with observations reported in previous investigations [3, 12].

4.2 Effect of injection timing

Fuel injection timing had a noticeable influence on idle emission characteristics. Compared with the 355° ATDC setting, the 350° ATDC injection timing generally resulted in lower CO emissions and a greater number of operating conditions satisfying the adopted idle emission limits. Earlier injection provides additional time for fuel evaporation and mixture preparation before ignition, which may contribute to improved combustion quality under idle operation [21].

The observed sensitivity of CO emissions to injection timing is consistent with previous optimization studies reporting fuel injection timing as one of the dominant parameters affecting exhaust emissions in electronically fuel-injected motorcycles [1, 24]. Although the present study did not directly evaluate in-cylinder mixture formation, the measured emission trends suggest that injection timing influenced combustion behavior through its effect on mixture preparation. This interpretation is further supported by the consistently lower CO emissions observed under the 350° ATDC injection timing across several fuel combinations.

4.3 Effect of ignition timing

Ignition timing also affected idle emission characteristics, although its influence depended on the selected fuel grade and injection timing. Under several operating conditions, moderate ignition advance produced lower CO and HC emissions than more advanced ignition settings. This finding indicates that the interaction between ignition timing and fuel injection timing plays an important role in determining idle combustion performance. Such interactions demonstrate that the effect of ignition timing cannot be considered independently from the accompanying fuel delivery strategy.

The operating condition that produced the lowest overall emissions in the present study combined 3° BTDC ignition timing with 350° ATDC injection timing using gasohol E40 (RON 98). While this combination exhibited the most

favorable emission characteristics among the investigated operating conditions, the present results are limited to idle operation and should not be interpreted as universally optimal for all engine loads or operating speeds. Previous investigations similarly reported that coordinated adjustment of ignition timing and injection timing contributes to improved combustion efficiency and lower exhaust emissions in spark-ignition engines [1, 3, 22].

4.4 Practical implications

From a calibration perspective, the present results indicate that idle exhaust emissions are influenced by the combined selection of fuel grade, ethanol blending ratio, ignition timing, and fuel injection timing. Within the investigated operating conditions, the 350° ATDC injection timing was frequently associated with improved emission performance, particularly when combined with appropriate ignition timing and higher-octane fuels. These findings provide experimental evidence that fuel properties and ECU calibration should be considered together when optimizing idle emission performance, consistent with previous studies emphasizing the importance of integrated fuel and engine calibration strategies for emission reduction [1, 12, 19, 22].

The present results may therefore serve as a practical reference for preliminary ECU calibration aimed at improving idle emission characteristics in electronically fuel-injected motorcycles. Nevertheless, because the present investigation was conducted only under steady idle conditions, additional studies covering wider engine operating conditions are required before these observations can be generalized to practical vehicle operation.

5. CONCLUSION

This study evaluated 27 idle operating conditions to examine the effects of fuel octane rating, gasoline–ethanol blend composition, ignition timing, and fuel injection timing on exhaust emission characteristics. The results indicate that compliance with the adopted idle CO and HC emission limits depended on appropriate combinations of fuel properties and ECU calibration under the investigated idle conditions.

Six principal findings were obtained. First, fuel grade was identified as a key factor affecting idle emission performance. Gasohol E10 (RON 92) satisfied the adopted idle emission limits under all evaluated ignition and injection timing combinations, whereas Gasohol E10 (RON 90) achieved compliance in only one of the four tested timing configurations and produced the highest HC emission when operated with 7° BTDC ignition timing and 355° ATDC injection timing. Second, two promising calibration strategies were identified. Gasohol E10 (RON 92) exhibited consistently compliant performance across the investigated timing settings, while Gasohol E40 (RON 98) combined with 3° BTDC ignition timing and 350° ATDC injection timing produced the lowest measured emissions, with CO and HC concentrations of 0.57 vol.% and 318.7 ppm, respectively. The 350° ATDC injection timing was frequently associated with improved emission performance, indicating that injection timing influenced idle combustion characteristics. Third, none of the Gasohol E40 (RON 92) operating conditions satisfied both adopted idle emission limits, suggesting that this fuel–timing combination was less favorable than the other evaluated configurations.

Fourth, operating conditions satisfying both emission limits generally exhibited AFR values between approximately 14.0 and 15.5, together with CO₂ concentrations above approximately 11.6 vol.% and residual O₂ concentrations below approximately 1.6 vol.%. Within the present dataset, compliant cases tended to cluster within these ranges, indicating an association between near-stoichiometric combustion and improved idle emission performance. Fifth, HC emissions showed greater sensitivity than CO emissions to variations in fuel properties and ECU calibration. Finally, the combination of Gasohol E10 (RON 90), 7° BTDC ignition timing, and 355° ATDC injection timing produced the least favorable emission performance among all evaluated operating conditions.

The present findings provide experimental evidence that fuel-specific ECU calibration can improve idle exhaust emission performance. In particular, the combination of Gasohol E40 (RON 98), 3° BTDC ignition timing, and 350° ATDC injection timing demonstrated the most favorable emission characteristics, whereas the consistently compliant performance of Gasohol E10 (RON 92) suggests greater calibration flexibility under idle operation. Conversely, the poorer performance observed for several low-octane fuel configurations indicates that additional calibration optimization may be required before practical implementation.

The conclusions of this study are limited to steady idle operation. Further investigations under cold-start, transient, and loaded engine conditions, together with evaluations of catalyst performance, fuel compatibility, engine durability, and real-world driving cycles, are necessary before broader engineering recommendations or regulatory implications can be established.

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REFERENCES

- [1] Purwanto, W., Maksum, H., Arif, A., Rochman, M.L., Sujito, S., Padrigalan, K.E. (2024). Exploration of engine parameters for emission reduction in gasoline-ethanol fueled engines. *Automotive Experiences*, 7(3): 486-501. <https://doi.org/10.31603/ae.12467>
- [2] Wahyudi, R., Purwanto, W., Maksum, H., Setiawan, M.Y., Sampurno, Y.G. (2023). The effect of electrolyzer installation on 4-stroke modified injection motorcycle on fuel consumption and exhaust gas. *Motivection: Journal of Mechanical, Electrical and Industrial Engineering*, 5(2): 415-426. <https://doi.org/10.46574/motivection.v5i2.238>
- [3] Purwanto, W., Firmansyah, M.S., Maksum, H., Arif, A., Setiawan, M.Y. (2024). Analysis exhaust emissions (CO, CO₂ and HC) on FI motorcycle with variations in ignition timing, injector timing and fuel variations. *BIS Energy and Engineering*, 1: V124033-V124033. <https://doi.org/10.31603/biseeng.80>
- [4] Aakko-Saksa, P., Koponen, P., Roslund, P., et al. (2020). Comprehensive emission characterisation of exhaust

- from alternative fuelled cars. *Atmospheric Environment*, 236: 117643. <https://doi.org/10.1016/j.atmosenv.2020.117643>
- [5] Sulisty, B., Sofyan, H., Sukardi, T., Widyanto, A. (2023). Performance and emission characteristics using dual injection system of gasoline and ethanol. *Automotive Experiences*, 6(2): 245-258. <https://doi.org/10.31603/ae.8070>
- [6] Sharma, N., Agarwal, A.K. (2020). Effect of fuel injection pressure and engine speed on performance, emissions, combustion, and particulate investigations of gasohols fuelled gasoline direct injection engine. *Journal of Energy Resources Technology*, 142(4): 042201. <https://doi.org/10.1115/1.4044763>
- [7] Al-Abboodi, N.K.F., Ridha, H. (2023). Review of compression ignition engine powered by biogas and hydrogen. *Power Engineering and Engineering Thermophysics*, 2(2): 57-72. <https://doi.org/10.56578/peet020201>
- [8] Meetam, K., Gonsrang, S., Dechwayukul, C., et al. (2023). Modeling and tuning of electronic throttle control system in formula student car. *International Journal of Automotive and Mechanical Engineering*, 20(4): 10917-10930. <https://doi.org/10.15282/ijame.20.4.2023.09.0844>
- [9] Hanifuddin, M., Taufiqurrahman, M.F., Setyawan, T.A., Anggarani, R., Wibowo, C.S., Sugiarto, B. (2023). Performance of a single-cylinder four-stroke engine with high concentrations of gasoline-ethanol-methanol (GEM). *Automotive Experiences*, 6(2): 407-415. <https://doi.org/10.31603/ae.9332>
- [10] Rashid, A.K., Mansor, M.R.A., Ghopa, W.A.W., Harun, Z., Mahmood, W.M.F.W. (2016). An experimental study of the performance and emissions of spark ignition gasoline engine. *International Journal of Automotive and Mechanical Engineering*, 13(3): 3540-3554. <https://doi.org/10.15282/ijame.13.3.2016.1.0291>
- [11] Yelbey, S., Ciniviz, M. (2020). Investigation of the effects of gasoline-bioethanol blends on engine performance and exhaust emissions in a spark ignition engine. *European Mechanical Science*, 4(2): 65-71. <https://doi.org/10.26701/ems.635790>
- [12] Adian, F., Sugiarto, B. (2020). The optimization of the relationship between octane number of gasoline-ethanol blend fuels in various settings of the engine control module. *Evergreen*, 7(4): 587-592. <https://doi.org/10.5109/4150510>
- [13] Huda, S., Purwanto, W., Wisesa, B.U. (2021). The effect of turbo cyclone installation on 4 stroke motor cycle on fuel consumption and exhaust emissions. *Motivection: Journal of Mechanical, Electrical and Industrial Engineering*, 3(2): 69-76. <https://doi.org/10.46574/motivection.v3i2.87>
- [14] Purwanto, W., Su, J.C.T., Rochman, M.L., Waluyo, B., Krismadinata, K., Arif, A. (2023). Study on the addition of a swirling vane to spark ignition engines fueled by gasoline and gasoline-ethanol. *Automotive Experiences*, 6(1): 162-172. <https://doi.org/10.31603/ae.7981>
- [15] Wahyu, M., Rahmad, H., Gotama, G.J. (2019). Effect of cassava biogasoline on fuel consumption and CO exhaust emissions. *Automotive Experiences*, 2(3): 97-103. <https://doi.org/10.31603/ae.v2i3.3004>
- [16] Syarifudin, S., Sanjaya, F.L., Fatkhurrozak, F., Usman, M.K., Sibagariang, Y. (2021). Effect methanol, ethanol, butanol on the emissions characteristics of gasoline engine. *Automotive Experiences*, 4(2): 62-67. <https://doi.org/10.31603/ae.4641>
- [17] Mendiburu, A.Z., Lauermann, C.H., Hayashi, T.C., et al. (2022). Ethanol as a renewable biofuel: Combustion characteristics and application in engines. *Energy*, 257: 124688. <https://doi.org/10.1016/j.energy.2022.124688>
- [18] Al-Muhsen, N.F., Hong, G., Ismail, F.B. (2021). Performance of combustion and emissions characteristics of ethanol dual injection spark ignition engine. *International Journal of Automotive and Mechanical Engineering*, 18(3): 9082-9093. <https://doi.org/10.15282/ijame.18.3.2021.20.0697>
- [19] Liu, Z., Sun, P., Du, Y., Yu, X., Dong, W., Zhou, J. (2021). Improvement of combustion and emission by combined combustion of ethanol premix and gasoline direct injection in SI engine. *Fuel*, 292: 120403. <https://doi.org/10.1016/j.fuel.2021.120403>
- [20] Heywood, J.B. (2018). *Internal Combustion Engine Fundamentals* (2nd ed.). New York, NY, USA: McGraw-Hill Education.
- [21] Baek, S., Cho, J., Kim, K., Myung, C.L., Park, S. (2021). Effect of engine control parameters on combustion and particle number emission characteristics from a SIDI engine fueled with gasoline-ethanol blends. *Journal of Mechanical Science and Technology*, 35(3): 1289-1300. <https://doi.org/10.1007/s12206-021-0240-x>
- [22] Purwanto, W., Firmansyah, M.S., Fajar, M., et al. (2025). Optimization of exhaust emissions on FI motorcycle using programmable ECU and ethanol mixture with taguchi method. *E3S Web of Conferences*, 622: 01015. <https://doi.org/10.1051/e3sconf/202562201015>
- [23] Mokhtar, M., Sugiarto, B., Agama, A.A., Kurniawan, A., Auzani, A.S. (2024). Investigating knocking potential, cycle stability, and emission characteristics in lean spark ignition engine with gasoline, ethanol, and methanol. *Automotive Experiences*, 7(1): 48-62. <https://doi.org/10.31603/ae.10607>
- [24] Firmansyah, M.S., Saputra, R., Febriansyah, I., et al. (2025). Effect of injector timing variations using a programmable ECU on exhaust gas emissions of FI motorcycles. *E3S Web of Conferences*, 622: 01019. <https://doi.org/10.1051/e3sconf/202562201019>

NOMENCLATURE

AFR	air-fuel ratio
ATDC	after top dead centre
BTDC	before top dead centre
CA	crank angle
CO	carbon monoxide
CO ₂	carbon dioxide
ECU	electronic control unit
E0	Pure gasoline (0% ethanol)
E10	Gasoline containing 10% ethanol (v/v)
E40	Gasoline containing 40% ethanol (v/v)
ESP	Enhanced Smart Power
FI	fuel injection
FID	flame ionization detector
HC	hydrocarbons
NDIR	non-dispersive infrared
O ₂	oxygen
ppm	parts per million

PGM-FI	Programmed Fuel Injection	STD	Standard factory ECU setting
RON	research octane number	vol.%	percent by volume
SOHC	single overhead camshaft		