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The Effect of Alcohol-Gasoline Blends on Exhaust Gas Emission Characteristics of Direct Injection Spark Ignition Engines

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Abstract
This study investigates the impact of alcohol-gasoline blends on the emission of harmful pollutants, including carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) from Direct Injection Spark Ignition (DISI) engines. With increasing global concerns over air pollution and the depletion of fossil fuels, alternative fuels such as alcohols have gained attention due to their renewable nature and lower carbon footprint. D-optimal Response Surface Methodology (RSM) design of Design Expert Software (13.0.1) with two factors (engine speed and engine load) and three responses (CO, HC and NO_X emissions) was used for the experimental design to determine the effect of alcohol-gasoline (methanol-ethanol-butanol-gasoline) blends on the exhaust gas emission characteristics of DISI engine. Four-stroke, single-cylinder DISI engine which was connected to a hydraulic dynamometer together with instrumentation panel and fuelled with pure gasoline, and two alcohol gasoline blends were used. The best fit model for each response was selected and analysis of variance was applied for a better understanding of model attributes. Results indicate that alcohol-gasoline blends lead to a significant reduction of 49.94% in HC emission, a 47.76% reduction in CO emission and a marginal increase of 0.79% in NOx emission compared to pure gasoline. Statistical analysis showed that all the models and model terms are significant and can therefore be used for accurate prediction. This study concludes that alcohol-gasoline blends present a viable option for reducing harmful emissions in DISI engines, but careful optimization of blend ratios and engine parameters are essential to balance performance and environmental impact.

Keywords: Direct Injection Spark Ignition, Alcohol-Gasoline Blends, Exhaust Gas Emissions, Dynamometer, and Fossil Fuel.

Introduction
The growing concerns over environmental degradation and the depletion of fossil fuel reserves have sparked extensive research into alternative energy sources for internal combustion engines. Conventional gasoline, while widely used, contributes significantly to the emission of harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM), which are major contributors to air pollution and global climate change (Heywood, 2018). The transportation sector is responsible for a significant portion of these emissions, particularly from spark-ignition engines, which are the primary power source for passenger vehicles worldwide (Elshenawy *et al*., 2023). The transportation sector, driven predominantly by internal combustion engines, contributes significantly to air pollution and greenhouse gas emissions. Spark ignition engines, which power the majority of passenger vehicles, are known to emit these harmful pollutants (Elshenawy *et al*., 2023). These emissions have adverse effects on human health and the environment, contributing to global warming, smog formation, and respiratory diseases. As regulatory bodies tighten emission standards worldwide, there is an urgent need to find alternative fuels or fuel additives that can mitigate the environmental impact of conventional gasoline engines (EPA, 2019).

In recent years, alcohol-based fuels such as methanol, ethanol and butanol have gained attention as viable alternatives or additives to gasoline. Alcohols are renewable, biodegradable, and have higher oxygen content than gasoline, which can lead to more complete combustion and thus reduced emissions of harmful pollutants (Lapuerta *et al*., 2018). In particular, alcohol-gasoline blends have been extensively researched for their potential to improve engine performance while simultaneously reducing the environmental impact of fuel combustion. Studies have shown that the addition of ethanol or methanol to gasoline can lead to significant reductions in CO and HC emissions due to the enhanced oxidation process during combustion (Karagoz *et al*., 2021). However, the impact of these blends on NOx emissions is more complex, often depending on the specific blend ratio, engine load, and operating conditions (Heywood, 2018). Some studies have shown that alcohol-gasoline blends may increase NOx emissions due to the higher combustion temperatures associated with alcohols (Karagoz *et al*., 2021). This presents a challenge in balancing the reduction of one type of pollutant with the potential increase in another, making it critical to optimize alcohol-gasoline blends to minimize overall emissions. (Liu, *et al*., 2018).

Direct injection spark ignition (DISI) engines have become increasingly popular due to their higher thermal efficiency and better fuel economy compared to conventional port-fuel injection engines. In a DISI engine, fuel is directly injected into the combustion chamber, allowing for greater control over the air-fuel mixture and combustion process, which can lead to improved performance and reduced fuel consumption (Zhou *et al*., 2016). However, DISI engines are also known to produce higher levels of particulate matter, a significant challenge in meeting increasingly stringent emission standards. The combination of alcohol-gasoline blends in DISI engines has not been extensively studied, especially concerning the detailed emission characteristics under varying operating conditions and alcohol blend ratios.

The objective of this study is to investigate the effect of alcohol-gasoline blends on the exhaust gas emissions of DISI engines. Specifically, this research aims to explore how varying concentrations of alcohol in the fuel blend affect the emissions of CO, HC and NOx, under different engine operating conditions. By analyzing the emissions characteristics of alcohol-gasoline blends, this study seeks to provide insights into the potential environmental benefits and trade-offs associated with using alcohol as a fuel additive in modern spark-ignition engines.

Materials and Methods

Alcohol-gasoline blend ratios were determined using the D-optimal Design in Mixture Methodology of Design Expert Software (version 13.0.1). Methanol, ethanol, butanol and gasoline were measured with different measuring cylinders and poured into a beaker. The mixture was then agitated vigorously to make a homogenous blend. Pure gasoline and two alcohol-gasoline blend samples were selected for use in the experiments, based on their physicochemical and fuel properties, which were the optimum blend (9.859% methanol, 5.0% ethanol, 5% butanol and 80.141% gasoline) and Blend-13 (5% methanol, 5% ethanol, 5% butanol and 85% gasoline).

D-optimal RSM design in Design Expert (13.0.1) was used for the experimental design to determine the effects of engine speed, and engine load on the exhaust gas emission characteristics of the DISI engine. The exhaust gas emissions of interest are oxides of Nitrogen (NOx), Carbon monoxide (CO) and unburned hydrocarbon (HC). The factors and the levels that were used are shown in Table 1. The experimental runs used as generated by the Design Expert are shown in Table 2.

Four-stroke, single-cylinder, Mazda MX-5, 92 kW DISI engine fuelled with Pure Gasoline (PG), Optimum Blend (OB) and Blend-13 (GB) was used in this study. DISI engine was connected to a hydraulic dynamometer (Figure1) with the help of coupling, and the set-up was mounted on a rigid frame. The hydraulic dynamometer (TD 115) was connected to an instrumentation unit (TD 114) designed to stand beside the engine under test. The instrumentation unit has a tachometer for measuring speed in rpm, torque meter for measuring torque in Nm, thermometer for measuring exhaust gas temperature, fuel measurement tube for measuring fuel consumption and airflow manometer for measuring air consumption (Ogunsola *et al*, 2023).

The exhaust gas emission level of the DISI engine was measured using NOVA 5460 series portable engine exhaust analyser to determine CO, HC, and NOx (NO and N_2O) emission levels when fuelled with pure gasoline, optimum blend and blend-13. The unit of measurement is Parts Per Million (PPM).

The independent variables (factors) were engine load and speed at three levels each. The dependent variables (responses) were CO emission, NOx emission and HC emission. The best-fit model for each response was selected and Analysis of Variance (ANOVA) was applied for a better understanding of model attributes. In ANOVA, F is a probability distribution in different samplings, Df is degrees of freedom and the *p*-value is a statistical measure of variations in samples of a particular property. The decision rule for significance was benchmarked as a *p*-value less than 0.05.

Table 1: RSM Design and Levels for Exhaust Gas Emission

Factors	Unit	Low (-1)	Level	
			Intermediate	High (+1)
Engine Speed	rpm	2500	3000	3500
Engine Load	%	0	50	100

The range of engine speed for an SI engine is usually between 2000 rpm to 4000 rpm (Heywood, 2018). In this study, engine speed was varied from 2500 rpm to 3500 rpm. The engine load was varied from zero loading condition (0% loading condition) to when the engine is fully loaded (100% loading condition) at three levels.

Table 2: RSM Design of Experiments for Exhaust Gas Emissions of DISI Engines

Run	Factor		Response		
	A: Engine Speed RPM	B: Engine Load %	HC Emission PPM	CO Emission PPM	NOx Emission PPM
1	2500	50			
2	2500	0			
3	2500	0			
4	3000	0			
5	3000	50			
6	3500	50			
7	2500	100			
8	3000	100			
9	3000	50			
10	3500	0			
11	3500	100			

Results and Discussion

The results of engine emission from DISI engine fuelled with Pure Gasoline (PG), optimum alcohol-gasoline blend (OB) and alcohol-gasoline blend (GB) were presented in Figures 2-4 and Tables 3-5. It can be seen from the figures and tables that HC and CO emissions increased with an increase in engine load and engine speed. The minimum HC emission of 403 ppm was obtained for the optimum alcohol-gasoline blend while emission of 805 ppm was obtained for pure gasoline at an engine speed of 2500 rpm and a load of 100%. This means there was a significant reduction of 49.94% in HC emission obtained for the optimum blend compared to pure gasoline. The reduction in HC emissions can be attributed to the more efficient combustion enabled by the oxygen-rich nature of alcohol fuels. The additional oxygen enhances the combustion process, ensuring that fewer hydrocarbons remain unburned. Furthermore, alcohols have higher flame speeds than gasoline, which facilitates a more complete combustion process and reduces the likelihood of hydrocarbon escape. These results are supported by Zutta *et al.* (2020), who found that alcohol-gasoline blends lead to substantial decreases in HC emissions due to enhanced combustion efficiency.

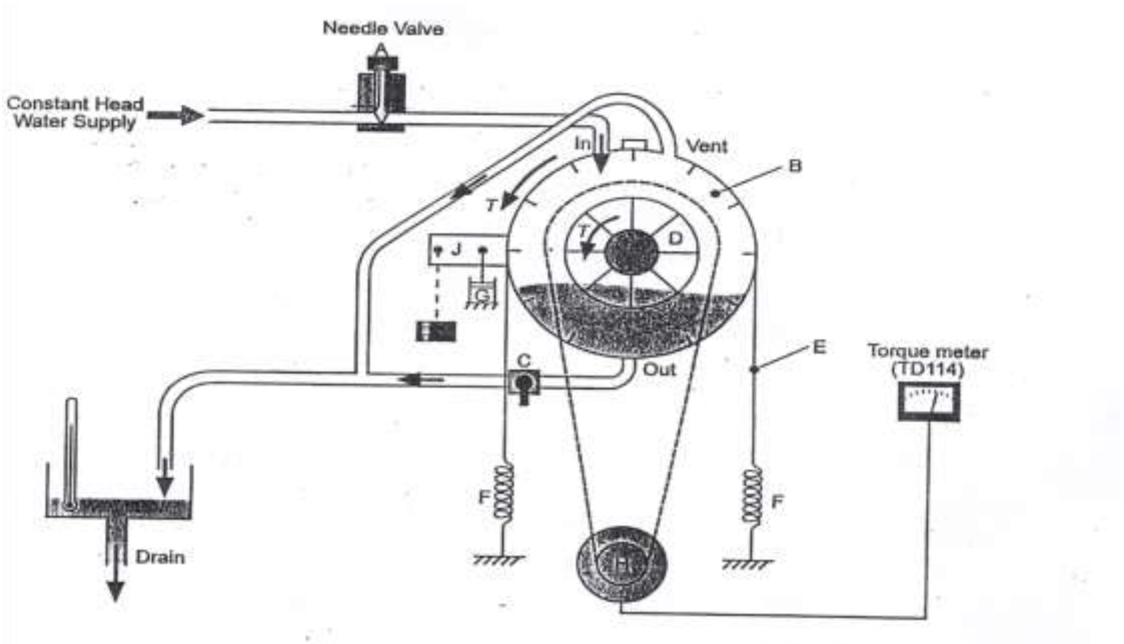

Figure 1: Schematic Diagram of Hydraulic Dynamometer
Source: Ogunsola *et al.* 2023

The minimum CO emission of 549 ppm was obtained for optimum blend while 1051 ppm was obtained for pure gasoline. This indicates a CO emission reduction of 47.76% for the optimum blend compared to pure gasoline. The reduction in CO emissions can be attributed to the higher oxygen content in alcohols, which promotes more complete combustion. Ethanol, methanol and butanol, being oxygenated fuels, improve the oxidation process, resulting in less incomplete combustion and thus lower CO formation. These findings align with studies conducted by Zutta *et al.* (2020), and Zhang *et al.* (2022), which also reported a decrease in CO emissions with increased ethanol and methanol content in gasoline.

NO_x emission increased with an increase in engine speed and engine load with a maximum value of 625 ppm obtained at speed of 3500 rpm and load of 100% for optimum blend. This may be because as speed and load increased, the cylinder temperature increased. This will cause higher NOx emissions since high temperature is one of the factors leading to the formation of NOx. The minimum NOx emission of 382 ppm was obtained for pure gasoline while 385 ppm was obtained for optimum blend. This is a marginal increase in NOx emission of 0.79% for the optimum blend compared with pure gasoline. The increase in NOx emissions can be explained by the higher combustion temperatures associated with alcohol-gasoline blends. Alcohols, especially ethanol, have a high latent heat of vaporization, which cools the intake air and increases the volumetric efficiency. However, once combustion occurs, the presence of additional oxygen leads to higher peak combustion temperatures, which favour NOx formation. These findings are consistent with previous research by Costa *et al.* (2021), Jiahong *et al.* (2022), and Akbiyik *et al.* (2023), who noted that NOx emissions tend to rise slightly with the introduction of alcohol into gasoline due to elevated combustion temperatures.

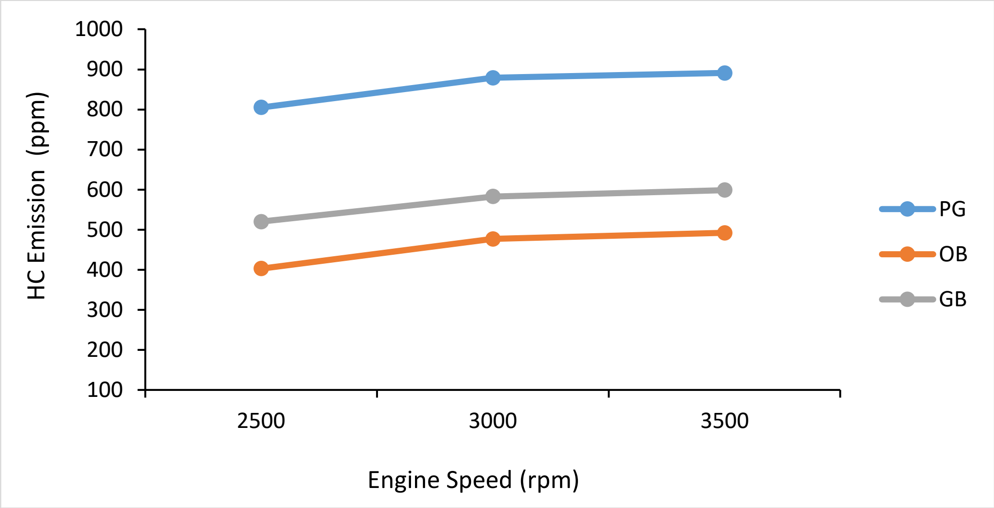

Figure 2: Effect of Engine Speed on HC Emission for Different Blend Ratios

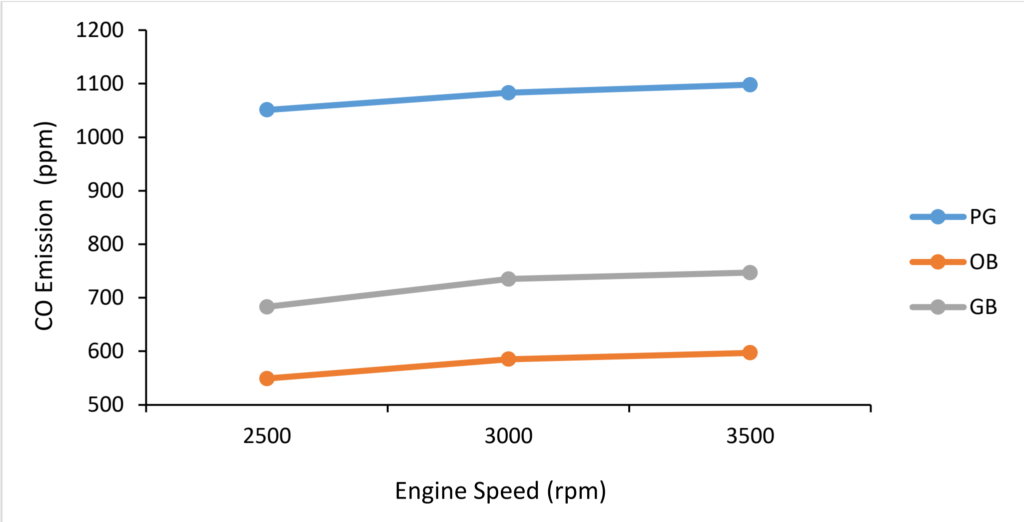

Figure 3: Effect of Engine Speed on CO Emission for Different Blend Ratios

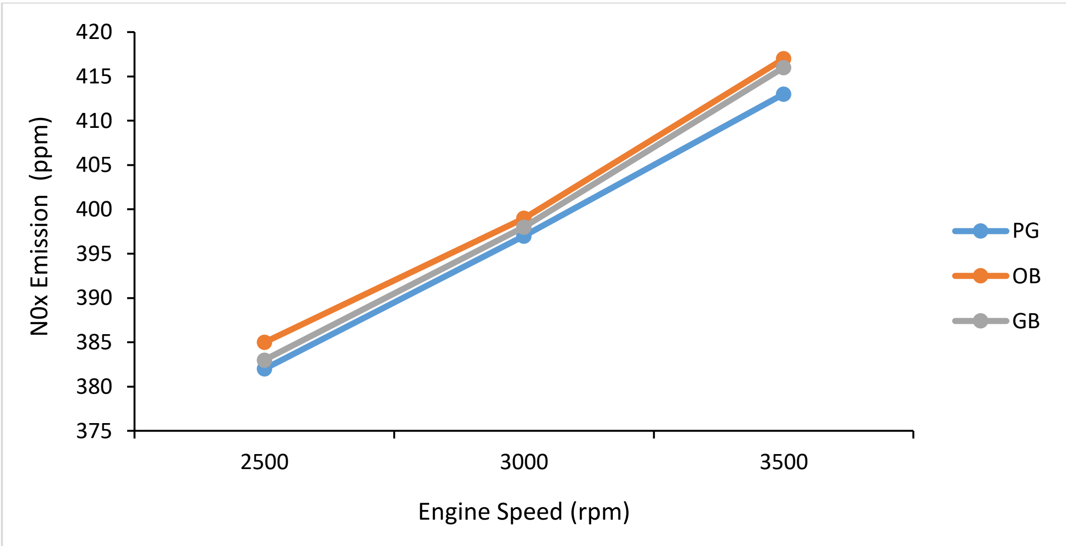

Figure 4: Effect of Engine Speed on NO_x Emission for Different Blend Ratios

Table 3: Effect of Engine Speed and Engine Load on Exhaust Gas Emission of DISI Engine Fueled with Pure Gasoline

Run	Factor		Response		
	A: Engine Speed	B: Engine Load	HC Emission	CO Emission	NOx Emission
	RPM	%	PPM	PPM	PPM
1	2500	50	925	1197	483
2	2500	0	805	1051	382
3	2500	0	805	1051	382
4	3000	0	879	1082	397
5	3000	50	957	1224	507
6	3500	50	982	1253	557
7	2500	100	1001	1398	592
8	3000	100	1105	1451	603
9	3000	50	957	1253	557
10	3500	0	891	1098	413
11	3500	100	1221	1578	621

Table 4: Effect of Engine Speed and Engine Load on Exhaust Gas Emission of DISI Engine Fueled with Optimum Blend

Factor		Response		
A: Engine Speed	B: Engine Load	HC Emission	CO Emission	NOx Emission
RPM	%	PPM	PPM	PPM
2500	50	526	693	486
2500	0	403	549	385
2500	0	403	549	385
3000	0	477	585	399
3000	50	556	723	509
3500	50	583	754	558
2500	100	602	894	596
3000	100	708	953	605
3000	50	556	723	509
3500	0	492	597	417
3500	100	820	1071	625

D-optimal design under the Response Surface Methodology (RSM) in Design Expert 13.0.1 software was adopted for model development and analysis of data. The effect of engine speed and engine load on the exhaust gas emissions of the DISI engine was evaluated. The models developed (equations 1-3) which are one quadratics and two linear were developed in terms of coded factors.

Table 5: Effect of Engine Speed and Engine Load on Exhaust Gas Emission of DISI Engine Fueled with Blend-13

Factor		Response		
A: Engine Speed	B: Engine Load	HC Emission	CO Emission	NOx Emission
RPM	%	PPM	PPM	PPM
2500	50	638	805	485
2500	0	520	683	383
2500	0	520	683	383
3000	0	583	735	398
3000	50	674	851	508
3500	50	698	906	558
2500	100	721	1019	598
3000	100	827	1101	604
3000	50	674	851	508
3500	0	599	747	416
3500	100	950	1221	624

The quality of the models developed was evaluated based on statistical methods and experimentation.

HC Emission = $573.53 + 58.61A + 124.28B$ (1)

CO Emission = $721.21 + 48.99A + 199.16B + 30.26AB + 4.08A^2 + 49.58B^2$ (2)

NO_X Emission = $509.07 + 21.88A + 103.88B$ (3)

Where A is engine speed and B is engine load

Table 6 shows that linear models are suggested for HC and NOx emissions while the quadratic model is suggested for CO emissions. The predicted R^2 values of 0.8471, 0.9586 and 0.9737 obtained for HC, CO and Nox emissions respectively are in reasonable agreement with their corresponding adjusted R^2 values of 0.9186, 0.9892 and 0.9840. High Adeq. Precision values of 19.8008, 37.4361 and 41.7902 obtained for HC, CO and NOx emissions respectively imply that the signal is adequate and the model is accurate and reliable. Table 7 showed that model F-values of 57.42, 184.49 and 308.66 were obtained for HC, CO and NOx emissions respectively. This means that the models are significant because there is only a 0.01% chance that F-values of this magnitude could occur due to noise. P-values of < 0.0001 obtained signify that all the model terms are significant since it is less than 0.05.

Table 6: RSM Model Summary Statistics for the Exhaust Gas Emission of DISI Engine

Properties	HC Emission	CO Emission	NOx Emission
Model	Linear	Quadratic	Linear
R^2	0.9349	0.9946	0.9872
Adj-R^2	0.9186	0.9892	0.9840
Pred R^2	0.8471	0.9586	0.9731
Adeq Precision	19.80008	37.4361	41.7902
C.V.	6.35	2.44	2.32
Std. Dev	35.37	17.95	11.53

Table 7: RSM Analysis of Variance (ANOVA) for the Exhaust Gas Emissions of DISI Engine

Properties	HC Emission	CO Emission	NOx Emission
Model	Linear	Quadratic	Linear
Sum of Squares	1.437×10^5	2.972×10^5	82003.85
DF	2	5	2
Mean Square	71840.78	59447.11	41001.92
F- Value	57.42	184.49	308.66
P- Value	<0.0001	<0.0001	<0.0001

Conclusions

This study investigated the impact of alcohol-gasoline blends on the exhaust gas emission characteristics of Direct Injection Spark Ignition (DISI) engines, with a focus on methanol, ethanol, butanol and gasoline blends. The results revealed that the use of alcohol-gasoline blends offers several significant advantages in terms of emission reduction, while also presenting challenges related to specific emissions.

i. The DISI engine emitted significant levels of carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC). These emissions varied with engine operating conditions, with higher loads and speeds generally resulting in increased emissions.
ii. There was a significant reduction of 49.94% in HC emission and a 47.76% reduction in CO emission obtained for the optimum alcohol-gasoline blend compared to pure gasoline.
iii. There was a marginal increase of 0.79% in the NO_X emission obtained for optimum alcohol-gasoline blend compared to pure gasoline.
iv. Statistical analysis showed that all the models and model terms are significant and can therefore be used for accurate prediction.
v. The use of alcohol-gasoline blends in DISI engines presents a viable pathway to reduce harmful exhaust emissions and lower specific environmental pollution costs, contributing to a cleaner and more sustainable automotive industry.

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