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Performance, emission, vibration and noise characteristics of gasoline-based fuel blends with JP-8, Jet A-1, and nitromethane mixtures in a single-cylinder gasoline engine

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ABSTRACT

This study investigates the performance, fuel consumption, and emission characteristics of various gasoline-based fuel blends, including JP-8 (Jet Propellant 8), Jet A-1, and nitromethane mixtures, in a single-cylinder, air-cooled, four-stroke gasoline engine. The engine was operated at a constant speed of 2500 RPM under varying torque loads (0 Nm, 2.5 Nm, 5 Nm, 7.5 Nm, and 10 Nm), and key performance indicators such as brake specific fuel consumption (BSFC), thermal efficiency, exhaust gas temperature (EGT), noise, vibration and exhaust emissions (CO, CO_2, NO_x, HC, O_2) were measured. The results revealed that blended fuels containing JP-8 and nitromethane exhibited improved thermal efficiency, especially under higher torque conditions. The highest thermal efficiency of 18.46 % was observed for the 90G5NM5JP8 blend at 10 Nm, compared to 16.67 % for pure gasoline (G100). Similarly, BSFC values significantly decreased with increasing load for all fuel blends, with 90G5NM5JP8 demonstrating the lowest BSFC at 458.17 g/kWh under 10 Nm load. In terms of emissions, NO_x levels increased with increasing load, with 90G5NM5JP8 reaching 2000 ppm at 10 Nm, indicating more combustion temperature. CO and HC emissions, on the other hand, decreased with higher loads for all blends, with 90G5NM5JP8 showing the lowest CO emissions at 3.026 % and HC emissions at 76 ppm. CO_2 emissions were higher for fuel blends containing Jet A-1 and nitromethane, reflecting more complete combustion. The study concludes that JP-8 and nitromethane blends significantly improve engine performance and efficiency but result in higher NO_x emissions. Experimental findings indicate that as engine load increases, vibration and noise levels rise across all fuel types. For G100 fuel, vibration increased by 191 %, from 33.49 m/s^2 at 0 Nm to 97.49 m/s^2 at 10 Nm. This increase was more pronounced in JP-8- and nitromethane-containing blends, with 90G10JP8 experiencing a 224 % rise, from 33.82 m/s^2 to 108.5 m/s^2 over the same load range. A similar trend was observed in noise levels, where G100′s noise increased by 8.2 %, from 90.01 dBA at 0 Nm to 97.37 dBA at 10 Nm. In contrast, the high-energy 90G5NM5JP8 blend exhibited a 9.1 % increase, reaching 99.13 dBA at 10 Nm. On the other hand, Jet A-1-based fuels demonstrated a relatively lower increase; for instance, 95G5JetA1′s vibration levels rose by 165 %, from 36.16 m/s2 to 95.83 m/s2. These findings suggest that these blends hold promise for high-performance applications, though further work is needed to manage emissions for broader practical use.

1. Introduction

Rising concerns about environmental pollution and global energy consumption have intensified the focus on alternative fuels for internal combustion engines. Gasoline engines, although efficient and widely used, contribute significantly to greenhouse gases and other harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and carbon dioxide (CO_2). Given increasing environmental challenges and stricter regulatory requirements, researchers are actively exploring alternative fuel options to reduce emissions and increase engine efficiency. Using alternative fuels or fuel mixtures may enable gasoline engines to operate more sustainably, ultimately contributing to cleaner air and reduced dependence on traditional fossil fuels [1–7]. A number of additives and blending strategies have been tested in gasoline engines to improve performance and emissions. For

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Nomenclature

°C	Degree Celsius
90G10JetA1	90 % gasoline + 10 % Jet A-1
90G10JP8	90 % gasoline + 10 % JP-8
90G5NM5JetA1	90 % gasoline + 5 % Jet A-1 + 5 % nitromethane
90G5NM5JP8	90 % gasoline + 5 % JP-8 + 5 % nitromethane
95G2.5NM2.5JetA1	95 % gasoline + 2.5 % Jet A-1 + 2.5 % nitromethane
95G2.5NM2.5JP8	95 % gasoline + 2.5 % JP-8 + 2.5 % nitromethane
95G5JetA1	95 % gasoline + 5 % Jet A-1
95G5JP8	95 % gasoline + 5 % JP-8
BSFC	Brake-specific fuel consumption
CH_3NO_2	Nitromethane
CO	Carbon monoxide
CO_2	Carbon dioxide
cSt	Centistokes
dBA	Decibel
EGT	Exhaust gas temperature
g/kWh	Grams per kilowatt-hour
G100	100 % gasoline (baseline fuel)
HC	Hydrocarbons
HCCI	Homogeneous charge compression ignition
Jet A-1	Kerosene type jet fuel
JP-8	Jet propellant 8
LHV	Lower heating value
LTC	Low temperature combustion
m/s^2	Metre per second squared
MJ	megajoules
Nm	Newton-meter
NO_x	Nitrogen oxides
PPM	Parts per million
RPM	Revolutions per minute
THC	Total hydrocarbons

example, methanol and ethanol have been widely studied because of their high oxygen content, which can promote more complete combustion and reduce CO and HC emissions. Studies indicate that ethanol-gasoline blends generally lead to increased NO_x emissions, while their effects on engine performance vary depending on the blend ratio, combustion characteristics, and engine load conditions [8–10]. Ethanol is an effective fuel additive that improves performance and reduces emissions in gasoline engines [11–20]. Methanol increases engine performance and reduces emissions when used in gasoline engines. Thanks to its high octane number, it is resistant to knocking and plays an important role in reducing environmental impacts. Methanol-gasoline blends increase engine performance and efficiency while significantly reducing emissions. However, it should be noted that methanol can increase NO_x emissions and that mixture stability must be ensured. In general, methanol has been studied in various studies as an effective and environmentally friendly alternative fuel for gasoline engines [2,21–29]. Toluene is another additive that has been investigated for its potential to improve engine power output due to its high octane number, but its effects on emissions can be mixed. The use of toluene in gasoline engines reduces particulate emissions while improving combustion efficiency [30–32]. However, it can increase THC and CO emissions. Toluene increases thermal efficiency at low engine speeds, while increasing NO_x emissions at high engine speeds to a lesser extent than other aromatic compounds [33]. Similarly, nitromethane is known to increase combustion intensity, increasing both power output and NO_x emissions, making it a useful additive for performance-oriented applications but potentially challenging for emissions control. The use of nitromethane in gasoline engines increases engine performance and torque while reducing specific fuel consumption and improving thermal efficiency. However, emissions are reduced for CO and HC, while CO_2 and NO_x are increased. The use of nitromethane in high concentrations can cause engine knocking and may require intermediary fuels such as methanol for mixture stability. Therefore, it is important to use nitromethane with caution and in appropriate proportions [34–37]. These studies show that while many fuel additives improve certain aspects of performance, each has unique effects on emissions that must be carefully managed. Jet A-1 fuel is being investigated for its potential to improve engine performance and reduce emissions in internal combustion engines. Various experimental and theoretical studies have been conducted to understand how this fuel performs in different types of engines and what advantages it offers. When used in gasoline engines, Jet A-1 fuel has produced higher power and torque than gasoline fuel in the 1900–3000 rpm range [38]. In diesel engines, when Jet A-1 fuel was used, the combustion phase was delayed and the premixed combustion fraction increased, resulting in a higher premixed heat release peak. Jet A-1 fuel has the potential to produce lower particulate matter (PM) emissions compared to diesel fuel. At low engine loads, higher nucleation particle concentrations were observed with Jet A-1 fuel, but these particles decreased and deposition particles increased as the engine load increased [39]. Additionally, adding water to Jet A-1 fuel reduced NO_x emissions and lowered exhaust gas temperature [40]. Adding various additives to Jet A-1 fuel can improve combustion and emission performance. For example, when blended with additives such as ethanol and pentanol, the oxygen content of the fuel increased, resulting in higher combustion rates and lower emissions. In addition, these blends increased thermal efficiency and reduced harmful gas emissions [41]. JP-8 (Jet Propellant 8) fuel in internal combustion engines is becoming widespread, especially in military and special purpose applications. Various studies have investigated the effects of this fuel on engine performance, combustion characteristics and emissions. JP-8 has a shorter spray tip penetration and a wider spray angle than diesel fuel. This is due to the faster evaporation properties of JP-8. The ignition delay of JP-8 is longer than diesel fuel. This is due to the lower cetane number of JP-8. While JP-8 produces less smoke than diesel fuel, it produces more HC and NO_x emissions [42,43]. By using EGR (exhaust gas recirculation) and multiple injection strategies, NO_x and PM (particulate matter) emissions can be halved with JP-8 [44]. JP-8 has a higher heat release rate and a larger premix combustion portion compared to diesel fuel. This is due to the superior mixing ratio of JP-8 [43]. Efficient combustion of JP-8 is possible in low compression engines, providing a suitable solution for military applications [45–47]. JP-8 can be used in low temperature combustion strategies (LTC) and homogeneous charge compression ignition (HCCI) engines, however, engine load is limited by knocking in these strategies [46,47]. Multiple injection strategies can be effective to optimize the combustion process of JP-8 [44,47]. The use of JP-8 in gasoline engines is being investigated as a single fuel strategy, particularly for military and emergency applications. This research aims to address the challenges of JP-8′s low vapor pressure and thermal decomposition. Due to the low vapor pressure of JP-8, the fuel must be heated to be used in gasoline engines. Heated JP-8 exhibits equivalent or superior ignition properties compared to gasoline. The flash vapor fuel injector was developed to solve the thermal decomposition (coking) problem of JP-8. This injector rapidly vaporizes JP-8, improving engine performance [48]. The use of JP-8 causes a slight performance reduction (2–5 %) in diesel engines. However, NO_x emissions are reduced by 15–26 % [49]. Higher levels of fuel dilution in the oil have been observed in JP-8 powered engines compared to gasoline powered engines. This can affect the long-term reliability of the engine [50].

Specific studies on Jet A-1, JP-8 and nitromethane have highlighted their potential as gasoline fuel additives. Jet A-1 and JP-8, kerosene-based aviation fuels with high energy content and stable combustion properties, show promise in improving gasoline engine thermal efficiency and fuel economy [51,52]. However, these aviation fuels may contribute to increased CO_2 emissions due to their complete combustion properties [53–56]. Nitromethane, a high-energy additive with high oxygen content, has been shown to increase power output and combustion efficiency despite a significant increase in NO_x emissions due to higher combustion temperatures [57,58]. The literature highlights the need to balance the results obtained in the use of these fuels, especially with improved engine performance and exhaust emission control.

Previous studies have examined the individual use of alternative fuels such as JP-8, Jet A-1, and nitromethane in internal combustion engines; however, limited research has explored their combined effects in gasoline-based blends. This study offers new perspectives by analyzing the synergistic impact of these fuel components on engine performance, emissions, vibration, and noise characteristics. As aviation fuels, JP-8 and Jet A-1 have higher energy density and distinct combustion properties than gasoline, potentially improving thermal efficiency and altering combustion dynamics. Meanwhile, nitromethane, known for its high oxygen content, influences combustion intensity, leading to variations in emissions and operational stability. By systematically evaluating these blends under varying engine loads, this study advances the understanding of their collective influence on key performance metrics, addressing gaps in existing literature and highlighting both the benefits and challenges associated with their practical applications.

This study aims to investigate the combined effects of Jet A-1, JP-8, and nitromethane with gasoline-based fuel blends in a single-cylinder gasoline engine, focusing on performance, fuel consumption, emissions, vibration, and noise characteristics under varying torque conditions. Unlike previous studies that examined these fuels individually or in simpler blends, this research comprehensively evaluates their combined effects, potentially revealing synergistic benefits that enhance engine performance metrics such as brake-specific fuel consumption (BSFC), thermal efficiency, and combustion stability. What differentiates this study from the existing literature is its detailed analysis of these fuel blends under real-world operating conditions, emphasizing high-torque scenarios.

In addition to evaluating engine performance and emissions, this research also investigates the impact of these alternative fuel blends on engine vibration and noise behavior. Given that fuel composition significantly influences combustion characteristics, this study aims to determine how these blends affect engine durability and user comfort by assessing vibration intensity and noise levels. By simultaneously addressing performance, emissions, vibration, and noise, this study provides valuable perspectives on the development of high-performance yet environmentally sustainable fuel formulations while considering their implications for engine operational stability and noise reduction strategies.

2. Material and methods

This section details the experimental procedures employed to investigate the effects of JP-8, Jet A-1, and nitromethane blended with gasoline on engine performance and exhaust emissions. The study was conducted using a single-cylinder, air-cooled, four-stroke gasoline engine. The experimental setup, fuel mixtures, engine testing procedure, and measurement methods are described below.

Table 1
Engine Specifications.

Features	Statement
Brand&Model	Honda GX200
Bore × stroke (mm × mm)	68 × 54
Cylinder volume (cm^3)	196
Number of cylinders	1
Cooling type	Air-cooled
Max. power (Hp, @3600 RPM)	6.5
Max. torque (Nm, @2500 RPM)	13.24
Compression ratio	8.5:1

2.1. Engine properties

The experiments were carried out using a single-cylinder, air-cooled, four-stroke gasoline engine (Honda GX200), the specifications of which are detailed in Table 1. This engine is widely used in small power applications and provides a reliable platform for testing various fuel blends due to its consistent performance characteristics.

The engine was operated at a constant speed of 2500 RPM, with engine loads varying between 0 Nm, 2.5 Nm, 5 Nm, 7.5 Nm, and 10 Nm, controlled using a dynamometer. This setup allowed for precise control over engine load conditions, enabling accurate and consistent measurements of engine noise, vibration, fuel consumption, and exhaust emissions under a range of operational scenarios. A schematic view of the experimental setup is shown in Fig. 1. The tests were designed to evaluate how different fuel blends affected engine performance under varying load conditions.

2.2. Fuel mixtures

A total of nine fuel blends, all based on gasoline, were evaluated. These blends included varying concentrations of JP-8, Jet A-1 and nitromethane combined with gasoline. The specific fuel mixtures, detailed in Table 2, range from pure gasoline (G100), serving as the baseline fuel, to various blended formulations with different proportions of additives. The blends were carefully prepared in the laboratory by precisely measuring the required volumes and thoroughly mixing them to ensure uniformity.

The fuel mixtures were prepared by carefully measuring the required amounts of each fuel component using a calibrated 0.1 g precision scale to ensure accurate blending ratios.

Table 3 shows the fuel properties of gasoline, JP-8, Jet A-1, and nitromethane. These properties include density, lower heating value (LHV), viscosity, and others essential for analyzing engine performance and emissions. This is a key parameter for understanding fuel performance. The table lists energy in MJ/kg, but adding MJ/L would provide a more practical comparison, especially since these fuels differ in density. For example, nitromethane has much lower energy per kilogram but higher density, which impacts its volumetric energy density.

Table 3 compares the properties of gasoline, JP-8, Jet A-1 and nitromethane. In terms of chemical composition, gasoline consists of variable hydrocarbons such as $C_{6\text{-}12}H_{14\text{-}26}$, while JP-8 and Jet A-1 generally contain C_9-C_{16} alkanes. These two fuel types are kerosene-based and are suitable for aircraft. Nitromethane, on the other hand, is a single-component, nitrogen-containing fuel with the formula CH_3NO_2; thanks to this feature, it releases oxygen during combustion, which increases engine performance. In terms of energy content, gasoline has a high energy density of 43.594 MJ/kg, which makes it suitable for use in vehicles with high energy needs, such as automobile engines. JP-8 and Jet A-1 also have energy contents close to gasoline; 43.3 MJ/kg

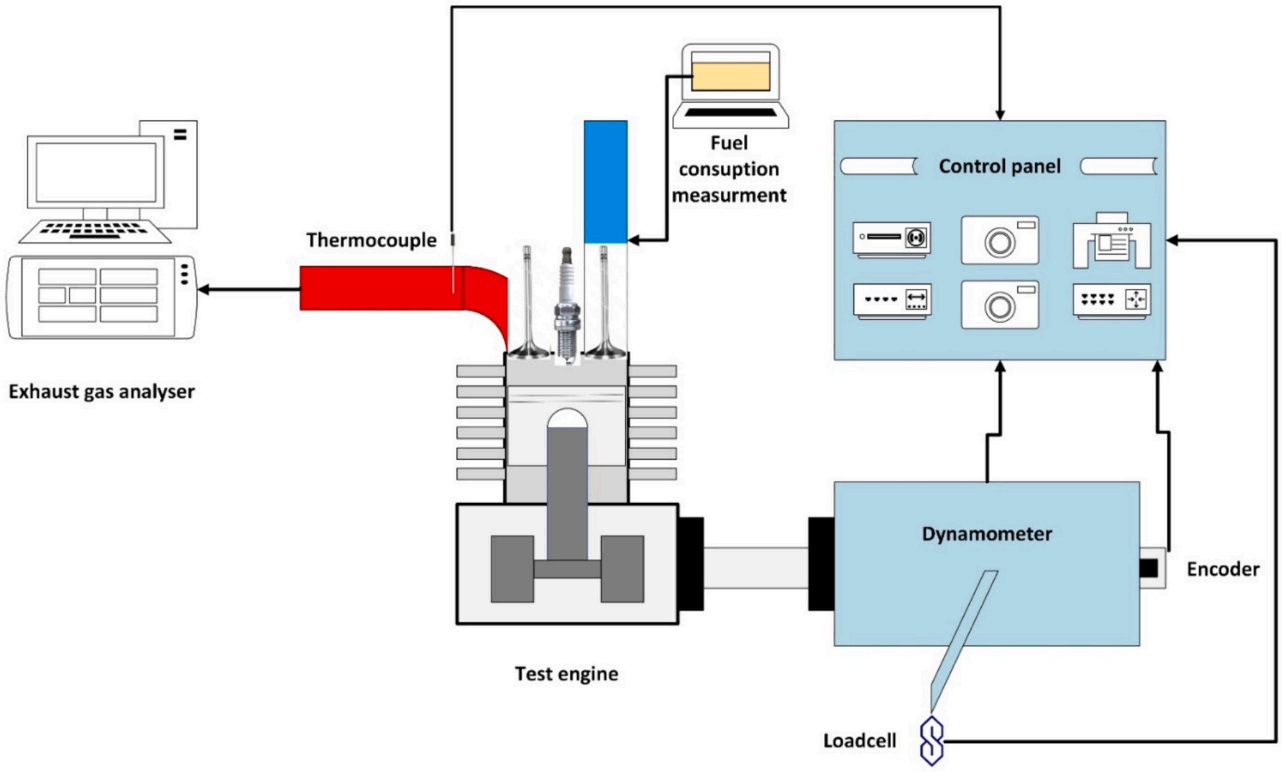

Fig. 1. Experimental Setup Schematic Diagram.

Table 2
Prepared test fuel mixtures.

Fuel Name	Mean
G100	100 % gasoline (baseline fuel)
95G5JP8	95 % gasoline + 5 % JP-8
95G5JetA1	95 % gasoline + 5 % Jet A-1
95G2.5NM2.5JP8	95 % gasoline + 2.5 % JP-8 + 2.5 % nitromethane
95G2.5NM2.5JetA1	95 % gasoline + 2.5 % Jet A-1 + 2.5 % nitromethane
90G10JP8	90 % gasoline + 10 % JP-8
90G10JetA1	90 % gasoline + 10 % Jet A-1
90G5NM5JP8	90 % gasoline + 5 % JP-8 + 5 % nitromethane
90G5NM5JetA1	90 % gasoline + 5 % Jet A-1 + 5 % nitromethane

and 42.8 MJ/kg, respectively. These fuels are optimized for safe and stable combustion for jet engines. On the other hand, nitromethane contains only 11.3 MJ/kg of energy but provides an advantage in racing applications by providing extra oxygen during combustion. In terms of density, gasoline is 0.746 g/cm^3 and evaporates quickly due to its low density, which is ideal for spark ignition engines. JP-8 and Jet A-1 have densities of 0.8 and 0.775 g/cm^3 respectively, which are suitable for balanced combustion in jet engines and allow more energy to be carried in aircraft fuel tanks. Nitromethane has the highest density with a density of 1.13–1.14 g/cm^3, making it advantageous in energy storage in limited space in racing. The flash point indicates that gasoline has a very low value at −43 °C and ignites easily. Although this feature provides a rapid ignition for gasoline, it poses a risk in storage and transportation. The flash points of JP-8 and Jet A-1 are above 38 °C, which makes them safe to use as aviation fuel. Nitromethane has a flash point of 35 °C, which makes it safer in controlled racing conditions. When we look at their auto-ignition temperatures, we see that gasoline has a value of 257 °C, which makes it suitable for easy combustion in spark-ignition engines. The auto-ignition temperatures of JP-8 and Jet A-1 are around 210 °C, which allows jet engines to burn stably under high pressure. Nitromethane has a high auto-ignition temperature of 418 °C, which shows that it is resistant to uncontrolled combustion and enables controlled combustion in high-performance engines. In terms of boiling range, gasoline has a wide boiling range of 27–225 °C, which allows rapid evaporation but also increases evaporation losses. JP-8 and Jet A-1 boil in a narrower range (150–300 °C), which supports stable combustion at high altitudes. The boiling range of nitromethane is very narrow at 100–103 °C, which supports precise combustion control in racing engines. In terms of viscosity, gasoline has a low viscosity of 0.4–0.8 cSt

Table 3
Test Fuel Properties.

Property	Gasoline[59,60]	JP-8[4361]	Jet A-1[62]	Nitromethane[63]
Chemical Formula	$C_{6\text{-}12}H_{14\text{-}26}$ (approx.)	C_9–C_{16} alkanes	C_9–C_{16} alkanes	CH_3NO_2
Energy Content (MJ/kg)	43.594	43.3	42.8	11.3
Density (g/cm^3)	0.746	0.8	0.775	1.13–1.14
Flash Point (°C)	−43	> 38	> 38	35
Autoignition Temp (°C)	257	210	210	418
Boiling Range (°C)	27–225	150–300	150–300	100–103
Viscosity (cSt at 20 °C)	0.4–0.8	1.2	1.3	0.6
Freezing Point (°C)	−52	−47	−47	−29

at 20 °C, which allows fuel to flow easily through carburetors and injection systems. JP-8 and Jet A-1 have a viscosity of 1.3 cSt, which provides controlled fuel flow in jet engines. Nitromethane has a viscosity of 0.6 cSt, which allows rapid fuel flow in racing engines. Finally, in terms of freezing point, gasoline has a range of −40 to −60 °C, which allows gasoline to be used in cold climates. JP-8 and Jet A-1 have a freezing point of −47 °C, allowing aircraft to use fuel at high altitudes without freezing. Nitromethane has a freezing point of −29 °C, which is sufficient for racing conditions, but can have limitations in extreme cold. In summary, gasoline is optimized for spark-ignition engines with high volatility, low flash point, and high octane rating. JP-8 and Jet A-1 are designed for aviation with a focus on safety, density, and low vapor pressure. Nitromethane is a special fuel designed for high power output in racing, and provides superior performance in racing engines due to its oxygen release capacity. These different fuel properties are customized to application requirements in areas such as safety, ease of use, and performance.

2.3. Test setup and experimental procedure

A dynamometer was used to apply and measure the engine load during the tests. It allowed for precise control of load conditions, with incremental increases from 0 Nm to 10 Nm, to assess engine behaviour under different load scenarios. Fuel consumption was measured using a digital precision scale with an accuracy of 0.1 g. This system allowed for accurate measurement of the fuel mass consumed during each test cycle, ensuring reliable data for fuel consumption analysis. Exhaust emissions, including CO, CO_2, HC, and NO_x, were monitored using a Bilsa brand exhaust gas analyser. The emissions were recorded under each load condition to observe the impact of different fuel mixtures on exhaust gas composition. Vibration data were collected using a UNI-T UT315A vibration meter mounted on the engine block to capture vibration levels m/s^2. Vibration data were recorded along three axes (X, Y, and Z) and averaged to assess engine stability and smoothness during operation comprehensively. Noise levels were measured using a PCE 322A sound level meter placed 1 m away from the engine. Noise measurements were recorded in decibels (dBA), with data collected every second and averaged over a 2-minute period for each load condition. The engine was warmed up for 10 min using the G100 to stabilize operating conditions. The engine speed was fixed at 2500 rpm for all tests, and the engine was run at varying loads (0 Nm, 2.5 Nm, 5 Nm, 7.5 Nm, and 10 Nm) for each fuel mixture. The engine was purged with G100 fuel between tests to avoid contamination between fuel mixtures. After switching to a new fuel mixture, the engine was allowed to stabilize for 2 min before measurements were taken. At each load condition, measurements of exhaust gas emissions, fuel consumption, vibration, and noise levels were recorded.

The uncertainties associated with various measurements are detailed in Table 4, and their impact on the experimental results has been carefully analyzed. The accuracy and uncertainty of each measurement instrument were systematically evaluated using the root sum square (RSS) method to estimate the overall uncertainty in key performance parameters. Fuel consumption was measured using a precision scale with a sensitivity of 0.1 g and an uncertainty of ±1 %, ensuring reliable fuel usage data. Emissions of CO, CO_2, NO_x, and HC were monitored using a BILSA Emission Analyzer, with accuracies of ±0.1 % for CO and CO_2, ±5 ppm for NO_x, and ±2 ppm for HC, resulting in an overall emission measurement uncertainty of ±2 %. Noise levels were recorded with a PCE 322A sound meter, which had an accuracy of ±0.1 dBA and an uncertainty of ±1.5 %, while vibration measurements were taken using a UNI-T UT315A vibration meter, providing an accuracy of ±0.01 m/s^2 with a ±1 % uncertainty. The dynamometer, used to regulate and measure engine load, had a precision of ±0.01 Nm and an uncertainty of ±1 %, ensuring precise torque readings. Engine speed was recorded with a tachometer, accurate to ±10 RPM with an uncertainty of ±0.5 %. The uncertainty propagation formula quantified the total uncertainties in brake-specific fuel consumption (BSFC), exhaust gas temperature (EGT), emissions, vibration, and noise.

The results were analyzed to assess the impact of JP-8, Jet A-1, and nitromethane mixtures on engine performance parameters such as brake-specific fuel consumption (BSFC), thermal efficiency, exhaust gas temperature, and exhaust emissions (CO, CO_2, NO_x, and HC). Each test was repeated three times for reliability, and the average values were recorded. The results were compared to the baseline gasoline (G100) performance to determine the effectiveness of each blend in enhancing engine efficiency and reducing emissions.

This experimental procedure aimed to thoroughly evaluate the impact of JP-8, Jet A-1, and nitromethane blends with gasoline on engine performance and emissions. The data collected and analyzed provides valuable perspectives on the potential for using these blends to enhance engine efficiency while addressing environmental concerns related to emissions.

3. Experimental results

The brake-specific fuel consumption (BSFC) data from Fig. 2 reveals important trends regarding the fuel efficiency of various fuel blends under different engine loads. Across all fuel blends, there is a consistent decrease in BSFC as the engine torque increases from 2.5 Nm to 10 Nm. This trend is typical in internal combustion engines, where higher loads generally result in more efficient fuel usage due to improved combustion stability and greater power output per unit of fuel consumed. For example, for the G100 fuel, BSFC decreases from 1332.86 g/kWh at 2.5 Nm to 487.57 g/kWh at 10 Nm. Similar trends are observed for all fuel blends, such as the 95G5NM5JetA1 blend, where BSFC decreases from 1234.86 g/kWh at 2.5 Nm to 458.17 g/kWh at 10 Nm. Alternative fuel blends (JP-8, Jet A-1, and Nitromethane mixtures) tend to exhibit lower BSFC values compared to G100, particularly at higher loads. This

Table 4
Uncertainties and range for measurement device.

Measurement	Instrument	Accuracy	Uncertainty (%)
Fuel Consumption	Precision Scale (0.1 g)	±0.1 g	±1 %
Exhaust Emissions	Bilsa Emission	CO: ±0.1 %,	±2 %
Exhaust Emissions	Bilsa Emission	CO_2: ±0.1 %,	±2 %
Exhaust Emissions	Bilsa Emission	NO_x: ±5 ppm	±2 %
Exhaust Emissions	Bilsa Emission	HC: ±2 ppm	±2 %
Noise Levels	PCE 322A	±0.1 dBA	±1.5 %
Vibration	UNI-T UT315A	±0.01 m/s^2	±1 %
Engine Load	Dynamometer	±0.01 Nm	±1 %
Engine Speed	Tachometer	±10 RPM	±0.5 %
Brake Specific Fuel Consumption (BSFC)	Derived from Fuel Consumption & Power		±2.1 %
Exhaust Gas Temperature (EGT)	K-Type Thermocouple	±2 °C	±0.25 %

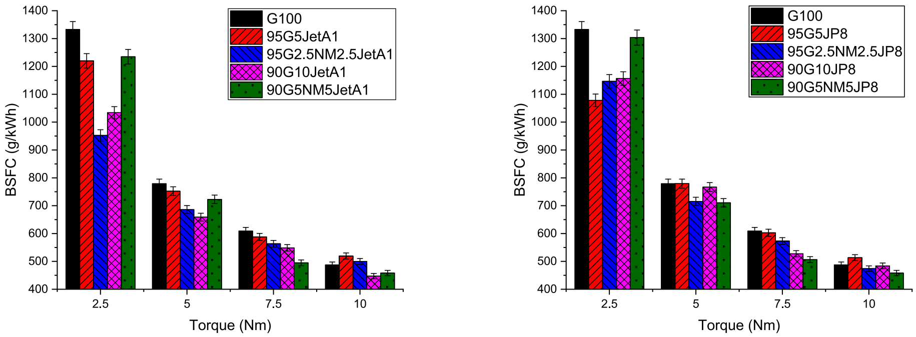

Fig. 2. BSFC variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

indicates that these blends perform better in terms of fuel efficiency when the engine is subjected to higher torque. For instance, at 10 Nm, 95G5NM5JP8 has a BSFC of 458.17 g/kWh, which is lower than G100 at 487.57 g/kWh, showing that nitromethane and JP-8 blends result in better fuel economy at this higher load. Fuel blends containing nitromethane (e.g., 95G5JP85N and 95G2.5NM2.5JetA1) consistently exhibit lower BSFC values than G100. Nitromethane, as a high-energy fuel, improves combustion efficiency, leading to lower BSFC values. For example, at 7.5 Nm, the 95G2.5NM2.5JetA1 blend has a BSFC of 563.53 g/kWh, compared to 609.26 g/kWh for G100. This suggests that adding nitromethane to gasoline significantly enhances fuel efficiency. Both JP-8 and Jet A-1 blends demonstrate improved BSFC performance across all torque levels compared to G100. This improvement is more pronounced at higher torque levels. For example, at 10 Nm, 90G10JP8 has a BSFC of 483.89 g/kWh, and 90G10JetA1 has an even lower BSFC at 447.14 g/kWh, both outperforming the G100 baseline fuel. This indicates that Jet A-1 and JP-8 offer superior fuel efficiency under higher loads. At moderate torque levels, such as 5 Nm and 7.5 Nm, there is a noticeable improvement in BSFC for most of the fuel blends compared to lower torque (2.5 Nm). For instance, 90G10JP8 at 7.5 Nm has a BSFC of 527.59 g/kWh, while at 5 Nm it has a BSFC of 766.88 g/kWh. This trend indicates that these fuels perform most efficiently at moderate to high engine loads. G100 consistently has higher BSFC values across all torque levels compared to the alternative fuel blends. While it does show improved fuel efficiency at higher loads, it is still outperformed by the fuel blends with additives. For example, at 2.5 Nm, G100 has the highest BSFC at 1332.86 g/kWh, whereas other blends such as 95G5JP8 and 90G10JetA1 have much lower values of 1078.05 g/kWh and 1033.95 g/kWh, respectively. This trend suggests that alternative fuels are more efficient even at lower loads. The trends from the BSFC data indicate that alternative fuel blends, particularly those containing JP-8, Jet A-1, and nitromethane, result in more efficient fuel consumption compared to pure gasoline, especially at higher torque levels [57]. As torque increases, fuel efficiency improves across all blends, but the performance of JP-8 and Jet A-1-based blends becomes significantly better than gasoline. Nitromethane also contributes to improved combustion efficiency, leading to lower BSFC values, making these blends more suitable for higher load operations.

Fig. 3 shows the CO_2 emissions for various fuel mixtures and torque levels. Across all fuel mixtures, CO_2 emissions increase as torque levels rise. This trend is expected because, as engine load increases, more fuel is combustion, leading to higher CO_2 production. For example, in G100, CO_2 emissions increase from 6.727 % at 0 Nm to 11.326 % at 10 Nm, illustrating the direct relationship between fuel consumption and CO_2 emissions as engine load increases. 95G5JP8, 95G2.5NM2.5JP8, and 90G5NM5JP8 show higher CO_2 emissions compared to G100 at each torque level. This suggests that while these blends may improve other performance parameters (e.g., reducing other pollutants or enhancing power output), they result in more complete combustion, which naturally leads to higher CO_2 emissions. For instance, at 10 Nm, G100 has 11.326 % CO_2 emissions, while 90G5NM5JP8 records 12.42 %. This higher emission percentage suggests that the alternative fuel mixtures are facilitating more efficient combustion but consequently result in higher CO_2 output. JP-8-based blends, such as 95G5JP8 and 95G2.5NM2.5JP8, show slightly higher CO_2 emissions than G100, particularly at higher torques. For example, at 10 Nm, 95G5JP8 produces 12.098 % CO_2 emissions, higher than G100's 11.326 %, indicating more efficient fuel combustion but leading to increased CO_2 output. Jet A-1-based blends (such as 95G5JetA1 and 90G10JetA1) also show a trend of increasing CO_2 emissions with torque. At 10 Nm, 90G10JetA1 emits 12.43 % CO_2 compared to G100's 11.776 %, demonstrating that these blends also lead to slightly higher CO_2 emissions, likely due to improved combustion efficiency. 90G5NM5JP8, which contains nitromethane, shows consistently higher CO_2 emissions than pure gasoline at all torque levels. At 2.5 Nm, 90G5NM5JP8 produces 8.387 % CO_2 compared to G100's 7.264 %, illustrating that nitromethane's oxygen-rich composition supports more complete combustion, which leads to higher CO_2 emissions. This trend is consistent at higher torques as well, where 90G5NM5JP8 at 10 Nm emits 12.42 % CO_2, slightly higher than G100's 11.326 %. The nitromethane blend promotes more complete combustion, but as a consequence, releases more CO_2. At no-load (0 Nm), the G100 blend shows 6.727 % CO_2 emissions, while all alternative

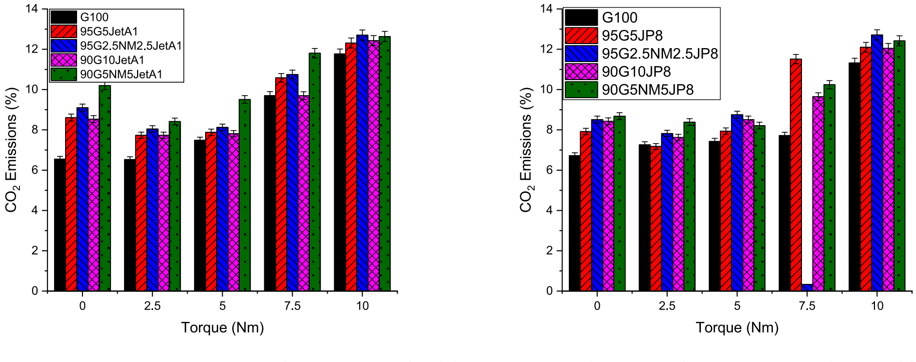

Fig. 3. CO_2 Emissions variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

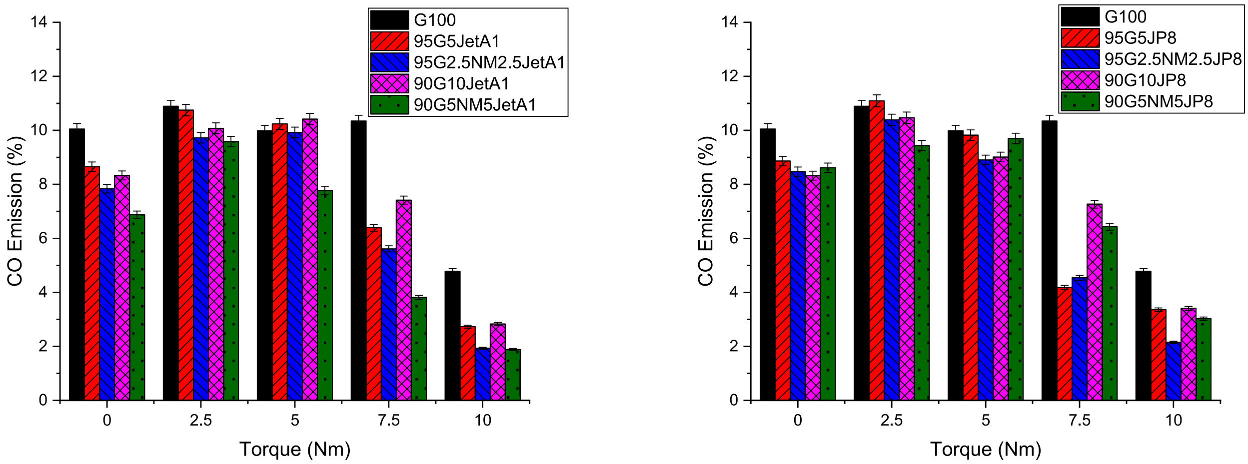

Fig. 4. CO Emissions variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

fuel blends produce higher CO_2 emissions. For instance, 95G5JetA1 produces 8.612 %, and 90G5NM5JP8 shows 8.68 %. This suggests that the alternative fuels combustion more completely even at no-load, resulting in higher CO_2 output. As torque increases, the differences between G100 and the alternative fuel blends become more pronounced, especially at 10 Nm, where most alternative fuels exhibit higher CO_2 emissions than pure gasoline. For example, 95G5JP8 produces 12.098 % CO_2, higher than G100′s 11.326 %. At low torque levels (e.g., 0 Nm and 2.5 Nm), alternative fuels show slightly elevated CO_2 emissions compared to G100, but the differences are less pronounced. At 2.5 Nm, G100 produces 7.264 % CO_2 emissions, whereas 95G2.5NM2.5JetA1 shows 7.821 %, which is only a minor increase. However, as the torque increases to 10 Nm, alternative fuels such as 90G5NM5JP8 exhibit much higher CO_2 emissions than G100. This suggests that these blends may be more efficient at higher engine loads, facilitating more complete fuel combustion. CO_2 emissions generally increase with engine load, as higher fuel consumption at greater torques results in more CO_2 production. This trend holds true for all fuel mixtures tested. Alternative fuels such as JP-8, Jet A-1, and nitromethane-based mixtures exhibit higher CO_2 emissions compared to pure gasoline across all torque levels [64]. This is likely due to the more complete combustion these fuels achieve, which increases CO_2 output. Nitromethane blends, like 90G5NM5JP8, show consistently higher CO_2 emissions, suggesting that nitromethane's oxygen content contributes to more complete combustion but at the cost of increased CO_2 production. Jet A-1-based fuels also show higher CO_2 emissions compared to G100, particularly at higher torque levels, which indicates their potential for more efficient combustion but with higher environmental impacts in terms of CO_2.

Fig. 4 shows the CO emissions for various fuel mixtures and torque levels. Across all fuel types, CO emissions decrease as the engine load (torque) increases. For instance, G100 starts with 10.051 % CO emissions at 0 Nm and drops to 4.785 % at 10 Nm. This trend is consistent across all fuel mixtures, indicating that higher engine loads promote more complete combustion, reducing the formation of carbon monoxide. The reduced CO emissions at higher torque can be attributed to better combustion conditions such as higher in-cylinder temperatures, which promote more efficient oxidation of carbon. In comparison to G100, most fuel mixtures with additives (e.g., 95G5JP8, 95G2.5NM2.5JP8, 90G10JP8, and 90G5NM5JP8) exhibit lower CO emissions at all engine torque. For example, at 0 Nm, 95G5JP-8 produces 8.863 % CO, which is lower than the 10.051 % observed for G100. Similarly, 90G5NM5JP8 shows 8.617 % at the same load level. At 10 Nm, 90G5NM5JP8 shows only 3.026 %, which is lower than G100′s 4.785 % at the same load. This suggests that the presence of nitromethane and JP-8 additives improves combustion efficiency, reducing the CO emissions across the load range. Fuel mixtures containing Jet A-1 and JP-8 fuels tend to have lower CO emissions than pure gasoline, especially at higher loads. For instance, 95G5JetA1 starts at 8.656 % at 0 Nm and drops to 2.73 % at 10 Nm, which is significantly lower than G100 at higher loads. This trend suggests that the introduction of Jet A-1 and JP-8 fuels enhances the fuel–air mixing and promotes more efficient combustion, leading to a reduction in incomplete combustion byproducts like CO. Fuels with nitromethane additives, such as 90G5NM5JP8, exhibit the greatest reduction in CO emissions as engine load increases. At 10 Nm, 90G5NM5JP8 shows only 3.026 % CO, compared to 4.785 % for pure gasoline. This reduction is largely due to nitromethane's oxygenated nature, which promotes more complete combustion. 95G2.5NM2.5JetA1, which also contains nitromethane, exhibits 2.15 % CO at 10 Nm, which is one of the lowest emissions values in the table, further illustrating the effectiveness of nitromethane in improving combustion and reducing CO emissions. At low engine loads (0 Nm to 2.5 Nm), all fuel types show higher CO emissions, with G100 having the highest emissions at 10.051 % at 0 Nm. This is expected since lower loads lead to incomplete combustion due to lower in-cylinder temperatures, which is a typical behaviour of gasoline engines. Even though alternative fuel mixtures show lower CO emissions than gasoline, they still exhibit higher emissions at lower loads compared to higher loads. At higher loads, particularly 10 Nm, the fuel blends containing Jet A-1 and nitromethane show the lowest CO emissions values. For example, 95G2.5NM2.5JetA1 shows 1.931 %, and 90G5NM5JP8 shows 3.026 %, which are both lower than pure gasoline and other blends. The inclusion of nitromethane improves combustion stability, contributing to these low CO levels by enhancing oxygen availability during combustion [37,65,66]. CO emissions decrease as engine load increases, with all fuel types exhibiting this trend due to improved combustion conditions at higher loads. Alternative fuel mixtures, particularly those containing nitromethane and Jet A-1, show lower CO emissions compared to pure gasoline across all engine loads, with the greatest reduction at higher loads. Nitromethane-containing blends show the most significant reductions in CO emissions, particularly at higher torque levels, indicating that these mixtures enable more complete and efficient combustion. Jet A-1 blends also demonstrate significantly lower CO emissions than pure gasoline, making them attractive candidates for reducing CO emissions in internal combustion engines.

The exhaust gas temperature (EGT) data from Fig. 5 reveals important trends regarding the fuel efficiency of various fuel blends under different engine loads. Across all fuel types, EGT increases as engine load increases. This trend is consistent, indicating that higher engine loads lead to higher combustion temperatures. For instance, with G100, the EGT rises from 560.1 °C at 0 Nm to 706 °C at 10 Nm. This is a typical observation for internal combustion engines, where increasing the load leads to more fuel being combusted, resulting in higher in-cylinder

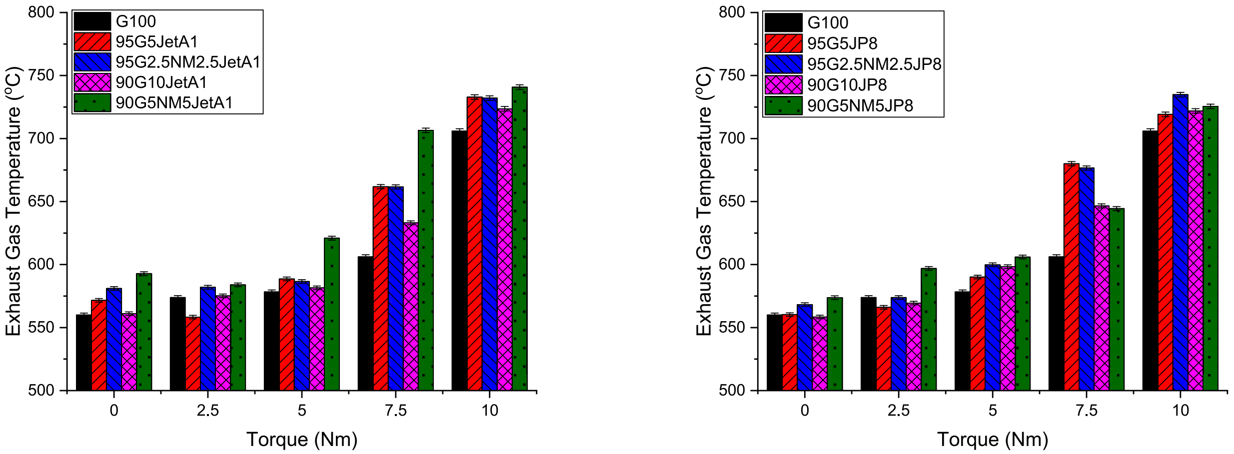

Fig. 5. Exhaust Gas Temperatur variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

temperatures and, consequently, higher exhaust gas temperatures. Fuel blends such as JP-8, Jet A-1, and nitromethane mixtures show higher EGT values compared to G100 at the same engine loads. For example, at 10 Nm, 90G5NM5JP8 shows 725.5 °C, 95G5JetA1 reaches 732.9 °C, and 95G2.5NM2.5JP8 reaches 734.8 °C, all higher than the 706 °C recorded for G100. This indicates that these fuel blends generally result in more complete combustion, leading to higher in-cylinder temperatures. Fuel mixtures containing nitromethane (e.g., 95G2.5NM2.5JP8, 90G5NM5JetA1) tend to produce the highest EGT values, especially under higher loads. This is due to the high energy content and oxygenation properties of nitromethane, which promote more complete and energetic combustion. For instance, 90G5NM5JetA1 reaches 740.8 °C at 10 Nm, one of the highest recorded temperatures, which implies that the presence of nitromethane and jet fuel contributes to higher combustion temperatures. There is a steady increase in EGT as engine load increases for all fuel types, regardless of the blend composition. This steady rise suggests that all fuels behave consistently under increasing mechanical stress, making the fuel blends predictable in terms of thermal response. For example, the 95G5JP8 blend starts at 560.3 °C at 0 Nm and rises to 719.2 °C at 10 Nm, following a smooth and consistent increase. The Jet A-1 blends, such as 90G10JetA1 and 90G5NM5JetA1, demonstrate efficient combustion, especially at higher loads. Their EGT values are comparable to nitromethane mixtures, indicating their potential for enhancing engine performance under high mechanical stress. 90G10JetA1 reaches 723.6 °C at 10 Nm, showing a stable and efficient combustion process across the load range. At lower engine loads (0 to 2.5 Nm), the EGT values are relatively lower across all fuel types, as expected. For example, G100 starts at 560.1 °C, and 95G5JetA1 starts at 571.6 °C at 0 Nm. This trend is consistent with less fuel being combusted and lower in-cylinder temperatures at lighter loads, leading to lower exhaust gas temperatures. The fuels demonstrate similar thermal response trends, with all fuel blends showing an increase in EGT with engine load, which implies that the fuel combustion process remains stable and reliable regardless of the specific fuel mixture. The differences are mainly in the absolute values of EGT, but the trend of increasing temperatures with load is consistent across all mixtures. Alternative fuel blends, particularly those containing nitromethane, JP-8, and Jet A-1, produce higher EGTs compared to pure gasoline, suggesting more complete and efficient combustion [67]. The Jet A-1 and nitromethane blends exhibit the highest EGT values, particularly under high load conditions, indicating enhanced combustion efficiency and performance potential. These trends highlight the ability of Jet A-1 and JP-8 based mixtures to improve combustion temperatures and potentially engine performance, particularly under higher mechanical stress.

Fig. 6 indicates hydrocarbon (HC) emissions for different fuel mixtures under various torque conditions. Hydrocarbon emissions are a key indicator of incomplete combustion, and a decrease in HC emissions suggests more efficient combustion. Across all fuel mixtures, HC emissions consistently decrease as engine torque increases. This is a typical behaviour as higher torque leads to more complete combustion due to higher cylinder temperatures and pressures, resulting in fewer unburned hydrocarbons. For instance, in G100 (pure gasoline), HC emissions drop from 1573 ppm at 0 Nm to 125 ppm at 10 Nm, showing a significant reduction as the load increases. At no-load (0 Nm), G100 shows the

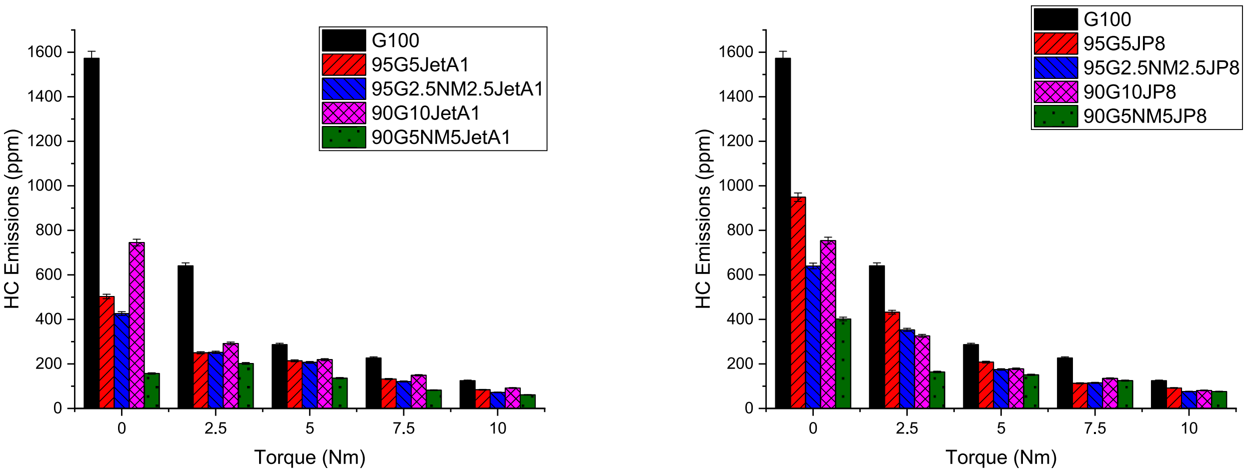

Fig. 6. HC Emissions variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

highest HC emissions at 1573 ppm, indicating incomplete combustion at low loads. All other fuel blends have lower HC emissions at this torque level, suggesting that alternative fuels promote better combustion efficiency than pure gasoline under no-load conditions. As the load increases to 10 Nm, G100 still shows higher HC emissions compared to some of the alternative fuels. For example, G100 has 125 ppm HC at 10 Nm, while 90G5NM5JP8 shows only 76 ppm, suggesting that the alternative blends (especially with nitromethane) improve combustion completeness at higher loads. JP-8-based fuels (95G5JP8, 95G2.5NM2.5JP8, 90G10JP8) show a notable reduction in HC emissions across all torque levels compared to G100. For example, 95G5JP8 has 92 ppm HC emissions at 10 Nm, which is lower than G100′s 125 ppm, demonstrating better combustion efficiency for JP-8 blends. At 2.5 Nm, 95G5JP8 has 432 ppm of HC emissions, much lower than G100′s 641 ppm, which further suggests that JP-8 blends can reduce unburned hydrocarbons, particularly at low to mid-range torques. Nitromethane blends (90G5NM5JP8) show the lowest HC emissions, particularly at higher loads. At 10 Nm, 90G5NM5JP8 records 76 ppm of HC emissions, indicating that the addition of nitromethane improves the overall combustion process and reduces incomplete combustion at high loads. Jet A-1 blends (95G5JetA1, 90G10JetA1) show a reduction in HC emissions compared to G100. For instance, 95G5JetA1 records 84 ppm at 10 Nm, while G100 shows 125 ppm, indicating better combustion efficiency with Jet A-1. At mid-range torques, JetA −1 blends also exhibit lower HC emissions compared to gasoline. For example, at 5 Nm, 90G10JetA1 has 219 ppm, while G100 has 287 ppm, which demonstrates the ability of Jet A-1 blends to improve combustion efficiency and reduce emissions. As expected, the increase in engine torque leads to a decrease in HC emissions for all fuel mixtures. This is due to higher engine load leading to more complete fuel combustion. At higher torques (7.5 Nm and 10 Nm), fuels like 90G5NM5JP8 and 95G2.5NM2.5JP8 show the lowest HC emissions, indicating that nitromethane and JP-8 blends can promote more efficient combustion at elevated loads. The consistent low emissions from these mixtures suggest their potential as cleaner fuel alternatives in high-performance or high-load engine conditions. Blends with nitromethane (such as 90G5NM5JP8) and Jet A-1-based mixtures (such as 95G5JetA1) show the lowest HC emissions across most torque levels, indicating superior combustion characteristics. Nitromethane, with its high oxygen content, promotes more complete fuel burning, which explains the significant reduction in HC emissions, particularly at higher loads. At 0 Nm, 90G5NM5JP8 has 402 ppm of HC emissions, much lower than G100′s 1573 ppm, showcasing nitromethane’s impact on enhancing combustion efficiency, even at no-load conditions. The general trend of decreasing HC emissions with increasing torque is consistent across all fuel mixtures, with alternative fuels showing better performance than G100 in reducing HC emissions. JP-8-based blends and nitromethane mixtures demonstrate a marked improvement in combustion efficiency, especially at higher loads, where HC emissions are significantly reduced compared to pure gasoline. Jet A-1 blends also show promising results in reducing HC emissions across all torque levels, further supporting the case for alternative fuels in internal combustion engines to reduce unburned hydrocarbons and improve combustion efficiency[41,68].

The observed reduction in HC and CO emissions with increasing engine load for fuel blends containing nitromethane and JP-8 can be attributed to their distinct combustion characteristics. As an oxygenated fuel, nitromethane (CH_3NO_2) provides additional oxygen, enhancing combustion efficiency and promoting more complete oxidation of hydrocarbons, thereby reducing HC and CO emissions. This effect becomes particularly pronounced at higher loads, where elevated combustion temperatures further facilitate complete fuel breakdown. Additionally, JP-8, a kerosene-based fuel, contributes to combustion stability due to its higher cetane number and improved evaporation properties compared to gasoline. The superior stability of JP-8 combustion results in smoother flame propagation and reduced cycle-to-cycle variations, leading to lower HC emissions. The combined effect of these properties explains why blends such as 95G2.5NM2.5JP8 exhibited the lowest HC (76 ppm) and CO (2.15 %) emissions at full load, supporting the conclusion that nitromethane and JP-8 improve combustion efficiency and emission performance under high-torque conditions.

Fig. 7 indicates NO_x emissions for different fuel mixtures under various torque conditions. Across all fuel blends, there is a clear trend of increasing NO_x emissions as the engine torque increases from 0 Nm to 10 Nm. This is expected, as higher torque and load conditions generally lead to increased combustion temperatures, which are the primary drivers for NO_x formation. For instance, NO_x emissions for G100 increase from 56 ppm at 0 Nm to 987 ppm at 10 Nm, showing a significant rise in emissions with load. Most of the alternative fuel blends, especially those containing JP-8, Jet A-1, and nitromethane, produce higher NO_x emissions compared to pure gasoline (G100). The 95G2.5NM2.5JP8 blend consistently shows high NO_x emissions, reaching 2011 ppm at 10 Nm. This suggests that the addition of JP-8 and nitromethane can lead to more complete combustion but also results in higher combustion temperatures, contributing to increase NO_x formation. Similarly, 90G5NM5JP8 and 95G2.5NM2.5JetA1 both reach 2000 ppm at 10 Nm, further indicating that blends with nitromethane tend to produce higher NO_x emissions due to the intense combustion characteristics of the additive. While some Jet A-1-based blends, such as 90G10JetA1, exhibit relatively lower NO_x emissions at lower loads (e.g., 22 ppm at 0 Nm and 33 ppm at 2.5 Nm), they still produce higher emissions as the load increases. For example, 90G10JetA1 reaches 1298 ppm at 10 Nm, which is higher than G100 but still lower than most JP-8-based blends. 90G5NM5JetA1 shows one of the highest NO_x emissions, reaching 2000 ppm at 10 Nm, suggesting that higher Jet A-1 content in the blend could lead to increased NO_x formation, especially at higher loads. The 95G5JP8 blend exhibits relatively moderate NO_x emissions compared to other JP-8-based blends. For example, at 7.5 Nm, 95G5JP8 shows 1026 ppm NO_x emissions, which, although high, is lower than 95G2.5NM2.5JP8 and 95G2.5NM2.5JetA1. This suggests that certain combinations of JP-8 and gasoline may offer a balance between

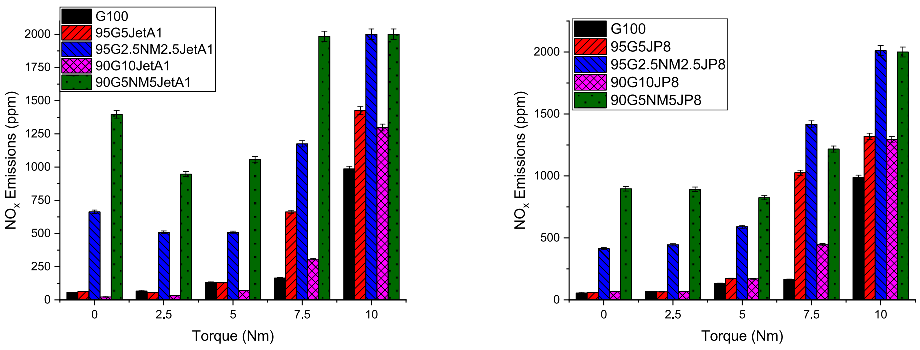

Fig. 7. NO_x Emissions variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

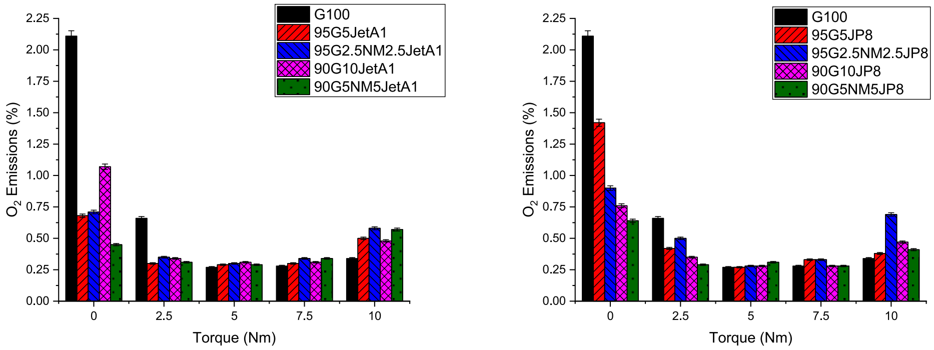

Fig. 8. O_2 Emissions variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

performance and emissions, though further optimization would be necessary to reduce NO_x emissions. Pure gasoline (G100) consistently has the lowest NO_x emissions across all torque levels compared to the alternative fuel blends. Even at the highest torque (10 Nm), G100 produces 987 ppm, which is lower than the NO_x emissions of all other blends except 90G10JetA1. This trend suggests that while gasoline may not be the most fuel-efficient option, it still outperforms many alternative fuel blends in terms of producing lower NO_x emissions. The trends identified from the NO_x emissions data indicate that alternative fuel blends containing JP-8, Jet A-1, and nitromethane tend to produce higher NO_x emissions compared to pure gasoline, particularly at higher torque levels. While these blends may offer improvements in fuel efficiency and performance, their higher combustion temperatures contribute to increased NO_x formation.[35,69] Blends like 90G10JetA1, which show lower NO_x emissions at moderate loads, may offer a compromise between efficiency and emissions, but further optimization of these blends would be required to minimize NO_x output while maintaining performance benefits.

Fig. 8 indicates O_2 emissions for different fuel mixtures under various torque conditions. Across all fuel mixtures, O_2 emissions generally decrease as engine torque increases. This trend suggests more complete combustion at higher loads, where the engine operates at higher temperatures and pressures, leading to more efficient fuel burning and less leftover oxygen in the exhaust gases. For example, in G100 (pure gasoline), O_2 emissions drop from 2.11 % at 0 Nm to 0.34 % at 10 Nm. This pattern of decreased oxygen levels at higher loads is consistently observed for most fuel blends. At low torque levels (0 Nm or no-load conditions), O_2 emissions are relatively high for all fuel blends. This suggests incomplete combustion at lower loads, where engine temperatures are lower, leading to a higher percentage of unburned oxygen in the exhaust gases. The highest O_2 emission at no-load condition is observed in G100 at 2.11 %, while the other blends exhibit lower values but still follow a similar trend of higher O_2 emissions at 0 Nm. JP-8-based blends (such as 95G5JP8, 95G2.5NM2.5JP8, and 90G10JP8) tend to show lower O_2 emissions compared to G100 at most torque levels, indicating better combustion efficiency. For instance, at 10 Nm, 95G2.5NM2.5JP8 shows 0.69 % O_2 emissions, which is higher than some of the other blends but lower than G100, reflecting the potential of JP-8 to promote more efficient combustion at higher loads. Blends containing nitromethane, such as 90G5NM5JP-8, show relatively low O_2 emissions at higher loads. For example, at 10 Nm, the O_2 emissions for 90G5NM5JP8 are 0.41 %, indicating that nitromethane enhances combustion efficiency, especially at higher engine loads. Nitromethane, known for its high oxygen content, contributes to more complete combustion, which explains the lower residual oxygen in the exhaust. Jet A-1 blends, such as 95G2.5NM2.5JetA1 and 90G10JetA1, exhibit varying O_2 emissions. While Jet A-1 blends tend to have lower O_2 emissions at higher loads (indicating efficient combustion), they show slightly elevated O_2 emissions at lower torque levels compared to other blends. For instance, 90G10JetA1 has 1.07 % O_2 emissions at 0 Nm, which is higher than some JP-8-based blends but decreases to 0.48 % at 10 Nm. Overall, the fuel blends containing JP-8 and nitromethane demonstrate more complete combustion, particularly at higher loads, with lower residual O_2 in the exhaust gases. This suggests these blends improve combustion efficiency compared to pure gasoline. The presence of oxygenated compounds like nitromethane contributes to more complete combustion, as seen in 90G5NM5JP8′s lower O_2 emissions at all torque levels. The primary trend is a general reduction in O_2 emissions as engine torque increases, indicating more efficient combustion at higher loads. Pure gasoline (G100) typically exhibits higher O_2 emissions compared to alternative fuel blends, particularly those containing JP-8 and nitromethane, which promote more complete combustion and thus result in lower oxygen emissions. This suggests that these alternative fuels improve combustion efficiency, especially at higher loads, where engines operate under more demanding conditions.

Fig. 9 shows thermal efficiency at varying engine loads across different fuel blends. Across all fuel types, thermal efficiency increases as torque increases. For instance, G100 shows an efficiency rise from 6.10 % at 2.5 Nm to 16.67 % at 10 Nm. This increase is consistent across all fuel blends, reflecting that engines generally operate more efficiently

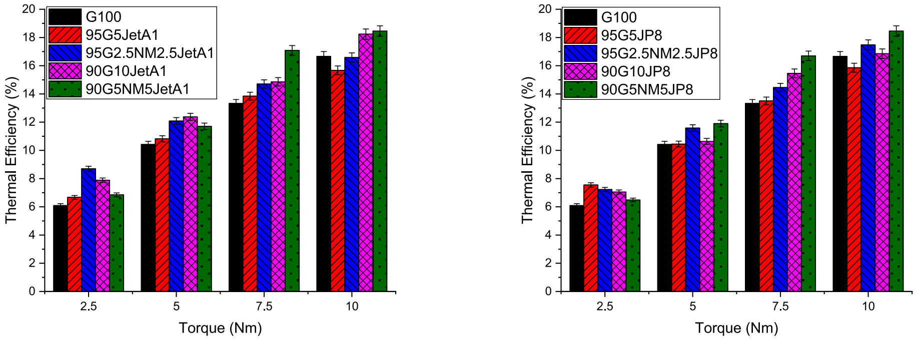

Fig. 9. Thermal efficiency variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

under higher loads due to more complete fuel combustion and optimized performance. Fuel mixtures containing JP-8 and nitromethane exhibit higher thermal efficiency compared to pure gasoline. For example, 90G5NM5JP8 shows the highest efficiency at 18.46 % at 10 Nm, surpassing G100′s 16.67 %. Nitromethane-enhanced blends, such as 95G2.5NM2.5JP8, also achieve superior efficiency values, with 17.48 % at 10 Nm, reflecting improved energy conversion and combustion quality due to the high energy content and oxygenating effect of nitromethane. Jet A-1-based blends also demonstrate good thermal efficiency, especially at higher torques. For example, 90G10JetA1 reaches 18.23 % at 10 Nm, which is comparable to the highest-performing JP-8 and nitromethane blends. At lower torque settings, Jet A-1 mixtures still maintain relatively high efficiency values, highlighting their potential as a strong alternative to gasoline. G100 (pure gasoline) consistently shows lower thermal efficiency compared to the fuel mixtures. At 10 Nm, its efficiency is 16.67 %, which is lower than most blended fuels. This suggests that pure gasoline's energy conversion is less effective, especially under high-load conditions, compared to fuels with added JP-8, Jet A-1, or nitromethane. Fuels containing oxygenates like nitromethane and high-energy fuels like JP generally outperform pure gasoline, particularly at higher loads. For example, 90G5NM5JP8 consistently shows higher efficiency, peaking at 18.46 %, which highlights the combustion stability and improved fuel energy release due to these additives. This demonstrates the positive effect of oxygenated fuels on thermal efficiency by allowing more complete combustion. At lower torque levels (2.5 Nm), the differences between fuel types are less pronounced, with efficiency values ranging from 6.10 % to 8.70 %. As the load increases, the more significant impact of fuel blends becomes apparent. This indicates that at low loads, the fuel type does not influence engine efficiency as much as at higher torque levels, where the engine can more fully utilize the energy content of the fuel. Thermal efficiency increases with torque for all fuels, reflecting more efficient engine operation at higher loads. JP-8 and nitromethane-enhanced fuels provide the highest thermal efficiency, particularly at high torque, suggesting that these fuels improve combustion quality and energy conversion [70]. Jet A-1 blends also offer competitive efficiency, particularly at higher torque, making them a viable alternative to gasoline. Pure gasoline exhibits lower thermal efficiency overall, underscoring the benefits of fuel mixtures for enhancing engine performance. The data suggests that oxygenated and high-energy fuels significantly improve thermal efficiency, especially at high loads.

Fig. 10 shows vibration level (m/s^2) at varying engine loads across different fuel blends. Across all fuel types, vibration levels increase consistently as engine load (torque) increases. This is expected due to higher mechanical stresses, increased combustion pressure, and engine activity at higher loads. For example, for G100 (pure gasoline), vibration increases from 33.49 m/s^2 at 0 Nm to 97.49 m/s^2 at 10 Nm. This trend holds for all other fuel blends as well, such as 95G5JP-8 increasing from 36.61 m/s^2 at 0 Nm to 105.8 m/s^2 at 10 Nm. Fuel mixtures containing JP-8 and nitromethane tend to exhibit higher vibration levels compared to pure gasoline. This is particularly noticeable at higher loads. For instance, at 10 Nm, 95G5JP8 results in 105.8 m/s^2, and 90G10JP8 produces 108.5 m/s^2, both significantly higher than G100, which generates 97.49 m/s^2 at the same load. Similarly, 90G5NM5JP8 shows a vibration of 102.2 m/s^2 at 10 Nm, demonstrating the greater mechanical stress induced by these high-energy fuel blends. Nitromethane-based blends such as 95G2.5NM2.5JP8 and 90G5NM5JP8 exhibit consistently higher vibration levels across all load conditions compared to gasoline and ethanol-based blends. For example, 95G2.5NM2.5JP8 shows 94.89 m/s^2 at 10 Nm, higher than G100 at the same load. This is due to the aggressive combustion characteristics of nitromethane, which can create more intense combustion pressures and thus higher vibration levels. Jet A-1-based blends, such as 95G5JetA1, generally show lower vibration levels compared to JP-8 and nitromethane blends. These fuels likely result in smoother combustion, leading to slightly lower vibrations. For instance, 95G5JetA1 produces 95.83 m/s^2 at 10 Nm, which is lower than the corresponding values for JP-8-based fuels like 95G5JP8 (105.8 m/s^2) and 95G2.5NM2.5JP8 (94.89 m/s^2). At low engine loads (e.g., 0 Nm and 2.5 Nm), the differences in vibration levels between fuel types are less pronounced. For example, at 0 Nm, the vibration values for all fuel types range between 33.49 m/s^2 and 38.98 m/s^2, showing only a slight variation. This suggests that fuel composition plays a more significant role in influencing vibration at higher loads, where the engine experiences more mechanical stress and combustion activity. Jet A-1-blended fuels like 95G5JetA1 and 95G2.5NM2.5JetA1 perform relatively well in terms of vibration levels. While they exhibit higher vibration than pure gasoline, their values are lower than the more volatile nitromethane and JP-based blends. For example, 95G2.5NM2.5JetA1 shows 103.14 m/s^2 at 10 Nm, which is higher than gasoline but lower than JP-8-based fuels. Engine load has a major influence on vibration levels, with vibration increasing consistently as load increases across all fuel types. JP-8-based and nitromethane blends exhibit higher vibration levels, particularly at higher engine loads, indicating greater mechanical stress and combustion intensity. Jet A-1-based blends demonstrate moderate vibration levels, suggesting smoother engine operation compared to JP-8 and nitromethane. At lower loads, the vibration differences between fuel blends are less pronounced, while at higher loads, the impact of fuel composition becomes more evident. These findings suggest that while fuel blends containing JP-8 and nitromethane may improve performance, they also result in higher engine vibration, which could affect engine durability and operational comfort in real-world applications [71].

Fig. 11 shows noise level measurements (dBA) at varying engine loads across different fuel blends. Noise levels rise for all blends as engine load (torque) increases. For example, with pure gasoline (G100), noise increases from 90.01 dBA at 0 Nm to 97.37 dBA at 10 Nm. This

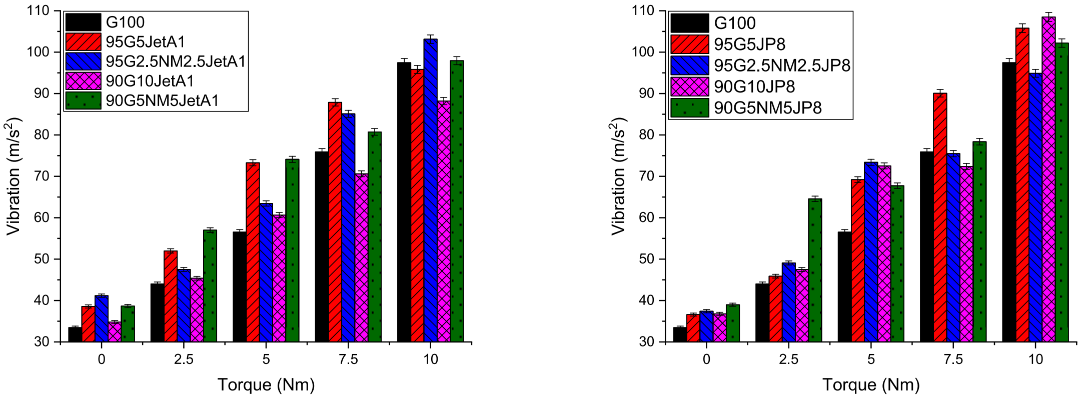

Fig. 10. Vibration level variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

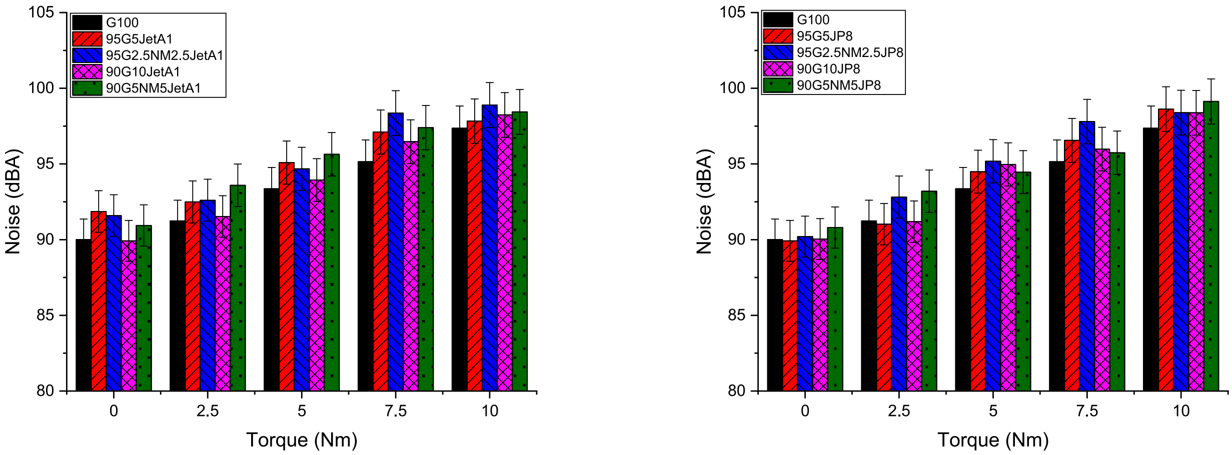

Fig. 11. Noise level variation according to engine load for mixtures with Nitromethane, Jet A-1 and JP-8 additions.

suggests that increased mechanical stress and combustion intensity contribute to the noise escalation as load intensifies. Blends containing alternative fuels, such as JP-8, Jet A-1, and nitromethane, generally produce higher noise levels than pure gasoline, particularly at higher loads. For instance, 90G5NM5JP8 reaches 99.13 dBA at 10 Nm, surpassing G100′s 97.37 dBA. This may stem from more intense combustion or higher in-cylinder pressures associated with these alternative fuels. Jet A-1-based blends exhibit slightly lower noise than JP-8 or nitromethane mixtures, suggesting more controlled combustion characteristics that slightly reduce mechanical noise. At lower loads (0 and 2.5 Nm), noise differences among fuel blends are minimal, with values ranging from 89.92 dBA (95G5JP8) to 90.94 dBA (90G5NM5JP8). However, as engine load increases, these differences become more noticeable. For example, at 10 Nm, JP-8-based blends produce notably higher noise, as seen with 95G2.5NM2.5JP8 recording 98.39 dBA compared to G100′s 97.37 dBA. This trend implies that while engine load is the primary factor affecting noise levels, fuel type plays a secondary role, with high-energy fuels contributing to increased noise emissions at elevated loads. These findings highlight that while alternative fuels can enhance engine performance, they may also elevate noise, which could be significant in noise-sensitive environments [72].

3.1. *Economic analysis*

The feasibility of alternative fuel blends in internal combustion engines is determined not only by their performance and emission characteristics but also by their economic viability. Traditional gasoline (G100) is generally priced between $3.00 and $4.00 per gallon, depending on market fluctuations and crude oil prices. Aviation fuels Jet A-1 and JP-8 are slightly more expensive, typically ranging between $3.50 and $5.00 per gallon. Since JP-8 is a military-grade fuel, its commercial availability is limited, potentially leading to higher procurement costs.

Table 5
Simplified fuel cost comparison per unit of energy produced.

Fuel Blend	BSFC (g/kWh)	% Change from G100	Estimated Cost ($/kWh)
G100 (Gasoline)	487.57	—	$0.11 – $0.15
95G5JP8	513.30	+5.28 %	$0.12 – $0.16
95G5JetA1	519.42	+6.53 %	$0.12 – $0.17
95G2.5NM2.5JP8	474.10	−2.76 %	$0.13 – $0.18
95G2.5NM2.5JetA1	499.82	+2.51 %	$0.12 – $0.17
90G10JP8	483.90	−0.75 %	$0.11 – $0.15
90G10JetA1	447.14	−8.29 %	$0.10 – $0.14
90G5NM5JP8	458.17	−6.03 %	$0.14 – $0.19
90G5NM5JetA1	458.17	−6.03 %	$0.14 – $0.19

Conversely, nitromethane is significantly more expensive, ranging between $30 and $50 per gallon due to its specialized production process, lower production volumes, and niche market demand (e.g., motorsports and industrial applications). While Jet A-1 and JP-8 provide similar energy density to gasoline, making them viable blending components without significantly increasing fuel consumption, nitromethane has a lower energy density, requiring higher volumetric consumption and leading to increased fuel costs.

A simplified fuel cost comparison per unit of energy produced (kWh) is presented in Table 5.

To assess the economic feasibility of these blends, brake specific fuel consumption (BSFC) data was analyzed. The 90G5NM5JP8 blend, which exhibited the lowest BSFC (458.17 g/kWh at 10 Nm), demonstrated better fuel efficiency compared to G100. However, the high cost of nitromethane significantly increases total fuel expenses, even at low blend percentages.

The results indicate that JP-8 and Jet A-1 blends offer a cost-competitive alternative to gasoline, while providing efficiency and performance benefits without significantly increasing fuel expenses. However, nitromethane inclusion substantially raises the fuel cost per energy unit, making it less suitable for widespread commercial use unless used in high-performance or aviation-related applications where cost is less critical.

Optimizing blend ratios to achieve the best balance between cost-effectiveness and performance improvements. Exploring alternative oxygenated additives that offer similar combustion benefits at a lower cost. Evaluating life-cycle costs, including fuel production, transportation, and emission-related costs, to assess overall economic impact. By balancing performance improvements with economic feasibility, this study provides guidance on selecting cost-effective fuel blends for various high-performance and aviation applications, ensuring both efficiency gains and affordability in practical use.

4. Conclusions

This study investigated the effects of JP-8, Jet A-1, and nitromethane fuel blends on a single-cylinder gasoline engine, analysing their impact on performance, emissions, vibration, and noise under varying torque conditions. The key findings are summarized as follows:

- Across all fuel blends, thermal efficiency increases with increasing torque. At the highest torque setting of 10 Nm, fuels containing JP-8 and nitromethane demonstrated the best performance. 90G5NM5JP8 exhibited the highest thermal efficiency at 18.46 %, followed closely by 90G10JetA1 and 95G2.5NM2.5JetA1. Pure gasoline (G100) showed the lowest thermal efficiency, especially under higher load conditions, where it reached 16.67 % at 10 Nm, suggesting that gasoline alone is less efficient compared to the fuel blends tested.

- BSFC values consistently decreased with increasing torque across all fuel mixtures, indicating improved fuel utilization as engine load increased. The 90G5NM5JP8 blend demonstrated the lowest BSFC value at 10 Nm with 458.17 g/kWh, highlighting the fuel's efficient energy conversion. Comparatively, G100 (pure gasoline) had higher BSFC values, indicating greater fuel consumption at all torque settings. This shows that fuel mixtures, particularly those with JP-8 and nitromethane, provide better fuel economy at higher loads.
- NO_x emissions increased significantly as the torque load increased. For example, 90G5NM5JP8 had the highest NO_x emissions at 2000 ppm at 10 Nm, reflecting the aggressive combustion of nitromethane and JP-8 in high-load conditions. Gasoline (G100) produced relatively lower NO_x emissions across all torque levels, suggesting that pure gasoline results in less NO_x formation due to its lower combustion temperature compared to the high-energy fuel blends.
- CO emissions decreased with increasing torque for all fuel blends, indicating improved combustion at higher loads. For example, G100 (pure gasoline) produced 4.785 % CO at 10 Nm, while 90G5NM5JP8 had lower CO emissions at 3.026 % under the same load, reflecting the cleaner combustion of the fuel blends. The fuel mixtures containing Jet A-1 and nitromethane generally had lower CO emissions compared to gasoline, suggesting a more complete combustion process, particularly at higher torque settings.
- HC emissions followed a similar trend as CO emissions, decreasing with increasing torque load. Pure gasoline (G100) had the highest HC emissions at 1573 ppm at 0 Nm, whereas fuel blends such as 90G5NM5JP8 exhibited much lower HC emissions (just 76 ppm at 10 Nm), indicating a more complete and efficient combustion process with these fuel mixtures. The significant reduction in HC emissions for the JP-8 and nitromethane blends suggests that these fuels promote better oxidation of hydrocarbons during combustion.
- CO_2 emissions increased with increasing torque, reflecting the higher levels of fuel combustion at higher engine loads. For instance, 90G5NM5JP8 showed 12.42 % CO_2 at 10 Nm, which is higher than pure gasoline's 11.326 % at the same load. The JP-8 and Jet A-1 fuel blends generally produced higher CO_2 emissions compared to pure gasoline, which is indicative of more complete combustion and higher energy release from these fuels.
- Exhaust gas temperature increased with torque for all fuels, as expected. The highest exhaust temperature was recorded for 90G5NM5JP8, reaching 725.5 °C at 10 Nm, suggesting the higher energy content and more intense combustion of the JP and nitromethane blends. G100 (pure gasoline) recorded lower exhaust gas temperatures, further supporting the conclusion that fuel blends result in more complete combustion and higher energy efficiency.
- Vibration levels also increased with torque for all fuel mixtures, with 90G5NM5JP8 showing the highest vibration level at 108.5 m/s^2 at 10 Nm. This is consistent with the high-energy combustion characteristics of the JP-8 and nitromethane blends, which tend to cause more aggressive combustion dynamics. Gasoline (G100) exhibited lower vibration levels across all torque settings, indicating a smoother combustion process compared to the blended fuels.
- Noise levels generally increased with higher torque, with 90G5NM5JP8 reaching the highest noise level of 99.13 dBA at 10 Nm. This is likely due to the higher energy release and more aggressive combustion of the JP and nitromethane mixtures. Pure gasoline produced lower noise levels, indicating a less aggressive combustion process compared to the fuel mixtures.
- The implementation of JP-8, Jet A-1, and nitromethane fuel blends in real-world scenarios presents both advantages and challenges. On the benefits side, these blends offer improved thermal efficiency and reduced brake specific fuel consumption (BSFC), making them attractive for aviation, motorsports, and military applications where fuel economy and performance optimization are critical. Additionally, the high oxygen content of nitromethane contributes to more complete combustion, potentially reducing carbon monoxide (CO) and hydrocarbon (HC) emissions under certain operating conditions. However, several challenges remain, particularly in terms of fuel availability, cost, and infrastructure compatibility. JP-8 and Jet A-1 are primarily used in aviation and military applications, and adapting these fuels for conventional gasoline engines would require modifications to the fuel system to account for differences in volatility, lubricity, and combustion characteristics. Furthermore, the higher NO_x emissions observed with these blends pose regulatory challenges for real-world use, necessitating the integration of aftertreatment technologies such as Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) to meet emission standards. Overall, while these fuel blends hold promise for high-performance applications, further research is required to optimize their use in commercial and automotive sectors, addressing both technical and environmental challenges to enhance their practicality.
- The feasibility of using alternative fuel blends in internal combustion engines depends not only on their performance and emission characteristics but also on their economic viability. The prices of JP-8, Jet A-1, and nitromethane vary based on market conditions, production costs, and availability. According to recent market data, Jet A-1 and JP-8 prices typically range between $3.50 and $5.00 per gallon, influenced by regional supply and demand, crude oil prices, and refining costs. Additionally, as a military-grade aviation fuel, JP-8 is less accessible for civilian applications, potentially leading to higher procurement costs. In contrast, nitromethane is significantly more expensive, with prices generally ranging from $30 to $50 per gallon due to its specialized production process and limited industrial demand. While its high oxygen content and combustion-enhancing properties make it an attractive fuel additive for increasing engine efficiency, its high cost and regulatory constraints limit its widespread adoption in conventional gasoline engines.

5. Recommendations

To better optimize the performance and emission effects of Jet A-1, JP-8, and nitromethane blends under high-torque conditions, it is recommended to test different mixing ratios. In particular, the impact of additives aimed at reducing NO_x emissions should be investigated.

This study was conducted on a single-cylinder engine. Testing the findings on different engine types (e.g., multi-cylinder engines or direct injection engines) would enhance the generalizability of the results.

The tests were conducted under controlled laboratory conditions. Investigating the performance and emission effects of these fuel blends under real-world driving conditions is essential for evaluating their practical applicability.

Comprehensive studies on the long-term impacts of using these fuel blends on engine performance, wear, and maintenance requirements are recommended.

To balance the increase in NO_x emissions, it is advised to examine the integration of post-exhaust emission control technologies (e.g., SCR catalysts) with these fuel blends.

Given the cost factors, optimizing fuel blends to balance economic feasibility with performance improvements remains an important area for further research. Future studies should explore alternative oxygenated additives that provide similar combustion advantages at a lower cost, ensuring a more sustainable and economically viable fuel solution.

CRediT authorship contribution statement

Miray İlgar Kılıçalp: Writing – original draft, Methodology, Data curation. **Usame Demir:** Writing – original draft, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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