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Investigating the Effect of CNG and LPG on the Engine Performance Parameters of a Petrol Engine

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ABSTRACT

In the present study, the results of an investigation on a direct injection engine using gasoline, CNG, and LPG are reported. The engine was operated at various speeds ranging from 1500 to 6000 rpm under four loading conditions (25%, 50%, 75%, and 100%). No modifications were made to the engine components or fuel injection system. A factorial analysis of variance (ANOVA) was conducted to examine multiple independent variables simultaneously and determine whether the effect of one factor (load) depended on another factor (speed). Additionally, a three-way ANOVA was performed to evaluate interaction effects. The results showed that engine power and exhaust gas temperature increased with engine speed under different loading conditions. Moreover, load increments had a significant impact on output power and torque. At full load, the power and torque of the engine increased by 5.4% and 3% when fueled with gasoline and LPG, respectively. The maximum torque of 102 Nm was observed at full load. Stronger combustion led to a rise in exhaust gas temperature at higher loads. Below 50% load, variations in engine speed had a limited effect on temperature. However, increasing rpm raised exhaust gas temperature, with a more pronounced effect at higher loads. ANOVA results indicated that fuel type did not significantly influence the relationship between power and torque as engine speed increased. Therefore, CNG and LPG can be used in internal combustion engines without significant performance losses.

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INTRODUCTION

Internal combustion engines, which are typically powered by fossil fuels like gasoline and diesel, can be adapted to run on bioenergy sources (i.e. biofuels) such as ethanol, biodiesel, and biogas. Fossil fuels have been the most important source of energy supply in the world in recent centuries (Fosudo et al., 2024). In 2021, 94% of the energy for the transportation sector in the United States, approximately 25 thousand trillion BTU, was obtained from fossil fuels. Globally, the transportation sector produces 37% of carbon dioxide emissions, consuming 20% of energy with 14% emission of greenhouse gases (Ağbulut et al., 2020). Today, petrol engines are used for long-term periods and various tasks, especially for transportation and electricity generation in greenhouses and livestock farms. In recent years, due to their high mechanical efficiency, these engines are also used for light tasks.

The biggest problem with using gasoline is that it is obtained from non-renewable fossil resources, and excessive extraction and refining have led to a decrease in the underground reserves (Darade & Dalu, 2013). On the other hand, given the large number of combustion engines present worldwide, global regulations to reduce pollution have intensified. For example, the emissions of Euro VI engines must reduce nitrogen oxides, methane, and particulate matter emissions by 75%, 55%, and 67%, respectively, compared to Euro V types (Grigoratos et al., 2016). Based on the Kyoto Protocol aimed at reducing greenhouse gas emissions and rapidly decreasing fossil fuel resources, more studies were carried out for alternative fuels and technologies that have cleaner and more economical combustion (Uslu et al., 2023). CNG and LPG are two important alternative fuels to gasoline, that can be produced abundantly worldwide (Darade & Dalu, 2013). It has been proven that spark-ignition internal combustion engines can effectively operate on these two gaseous fuels without the need for modifications (Sethiya, 2014).

Biofuels are considered renewable because they are derived from biological sources that can be replenished over time. This is in contrast to fossil fuels, which are finite and contribute to environmental problems like greenhouse gas emissions and climate change. The majority of biofuels are produced in the form of biogas and are obtained from organic materials like plants, algae, and animal waste. Biogas is one of the most attractive biofuels due to its easy availability, economical and easy to use in combustion engine while considering dual fuel mode (DFM) (Wang et al., 2016). Biogas is a clean fuel for internal combustion engines and it can be generated by cellulose biomass using anaerobic fermentation. In the oil crunch, it can be used as an encouraging alternative fuel, by replacing a substantial quantity of fossil fuels (Sharma et al., 2019). Biogas is the most effective and practical technique to use large spontaneous ignition temperature alternative fuels (Singh et al., 2018).

CNG, LPG and biogas share the key feature of being gaseous hydrocarbons that can be burned in internal combustion engines. The energy content and combustion properties of CNG and biogas are similar, which means that in many cases, engines designed for CNG can also be adapted to run on biogas (Yilmaz & Gumus, 2017). In regions where biogas is readily available (e.g., areas with agricultural waste or wastewater treatment plants), biogas can be used as a substitute for CNG in vehicles and engines with minimal modifications. Biogas-powered vehicles are increasingly being used in public transport and fleets, with biogas production facilities enabling the refueling of these vehicles.

LPG is a byproduct of oil refineries (Shipman, 2002), which composed of propane (C_3H_8) and butane (C_4H_{10}). This fuel, due to its gaseous phase at room temperature and lower density than gasoline and oily fuels, has a lower energy density, which is one of the disadvantages of this fuel (Momin et al., 2016). Its high octane number makes LPG suitable for using in petrol engines (Ashok et al., 2015). The abundant resources of LPG, its reasonable price, and lower greenhouse gas emissions made it as an ideal alternative to fossil fuels (Zhang et al., 2022). This fuel is converted to a liquid phase at a pressure of 0.8 MPa and ambient temperature. Also, its storage is simpler than that of other gaseous fuels (Tira et al., 2012). Due to its lower carbon content, LPG is introduced as a clean fuel that reduces carbon dioxide and other carbon pollutants compared to conventional fossil fuels (Kim et al., 2017).

From one to ten percent of raw gas has the potential to be converted into LPG through very simple and inexpensive processes. During the extraction of oil, LPG is also present in the produced gases. Given the large volume of this gas, it is often not possible to refine it, and approximately 140 billion cubic meters of LPG is burned in each extraction cycle to prevent gas poisoning. Therefore, the cost and energy required for LPG production are significantly lower than for diesel and gasoline. Unlike gasoline and diesel, 100% of LPG evaporates in the cylinder, there will be less efficiency drop in terms of the percentage of unburned fuel in the cylinder, which can be accompanied by lower fuel consumption in the cylinder (Paczuski et al., 2016).

CNG is obtained by compressing natural gas, which is mainly methane (CH_4). High-pressure cylinders with pressures ranging from 200 to 248 bar are used for its storage. The use of CNG reduces operational costs and also has less pollution compared to gasoline (MacLean et al., 2000). In terms of design components, there is no need for major changes to use gaseous fuels in petrol engines. By installing a fuel tank, gas transfer hoses, a regulator, a pressure gauge to control the gas pressure, as well as a valve for fuel entry into the engine's intake manifold, a gasoline engine can be converted to gas.

Gaseous fuels have a lower carbon-to-hydrogen ratio compared to gasoline. Burning them leaves less carbon and significantly reduces deposits in the combustion chamber, intake valves, piston crowns, and ring grooves, thereby greatly decreasing the possibility of damaging to the components. Additionally, the engine oil and its filter remain cleaner for gas fuels compared to gasoline, which reduces the time for their replacement and consequently lowers the operating costs. These advantages indicate an increased lifespan of the engine when using gas fuels compared to gasoline. Gaseous fuels, having a lower density compared to liquid types and can be easily pumped. So that they can be provided to consumers in farms, greenhouses, and remote rural areas much faster, easier, and cheaper than transporting liquid fuels.

In the late 1950s, companies began to produce LPG cylinders for household use. Vehicles powered by CNG have been in use since the mid-1930s. Considering the numerous gasoline engines in Iran, the use of gas fuels could be the best solution to reduce the rising trend of gasoline consumption and decrease their pollution. Additionally, according to the head of public relations at the oil distribution company in Qom province, the increase in gasoline prices and the implemented rationing have significantly boosted the use of gas fuels. LPG has been examined as a fuel in diesel engines, revealing issues such as low thermal efficiency at low engine loads. Moreover, at very low loads, significant hydrocarbon emissions were observed in the diesel engine using LPG (Ashok et al., 2015).

The most important performance parameters of an engine, as the main factor in carrying out the various tasks and the source of motion, are its power and torque. Therefore, in order to examine the impact of fuel usage on the capability of engines to run under different operating conditions, it is necessary to study the variations in the performance characteristics of petrol engines using gaseous fuels and ensure the adequacy of the power produced by these types of fuels. In a study, the power and torque of an engine were compared using gasoline and CNG at loadings of 50% and 100% (Aljamali et al., 2014). It showed greater power and torque for gasoline compared to CNG, and a slight increase in the power and torque was observed at 100% loading compared to 50%. Due to the great variety of operating conditions for internal combustion engines, examining only 50% and 100% loads is not sufficient, and it is also necessary to analyze 25% and 75% loads. On the other hand, examining gasoline, CNG, and LPG under the same experimental conditions can significantly aid in identifying the strengths and weaknesses of gaseous fuels. Also, considering that gaseous fuels combustion does not undergo the evaporation process in the engine cylinder, which is endothermic, it is expected that the combustion temperature in the cylinder when using these fuels will be higher than that of gasoline (Mistry, 2005). The higher combustion temperature for these fuels may cause problems for the moving parts of the engine, especially the cylinder, piston, exhaust manifolds, exhaust chamber and muffler.

Thus, the thermal shocks resulting from the heating and cooling of the engine in successive combustion cycles will be greater and can reduce the lifespan of the engine components. For this reason, investigating the combustion temperature of engines using gaseous fuels is essential to determine its impact on the health of the engine's moving parts. Considering the mentioned points, the goal of this study is to examine the power, torque, and exhaust gas temperature using gasoline, CNG, and LPG at different speeds and load conditions.

MATERIALS AND METHODS

The gasoline used in this experiment meets the Euro 5 standards. The specifications of the engine used are provided in Table 1.

Table 1. The engine specifications

Model	PIAGGIO
Cylinder no.	4
Stroke	88 mm
Bore	95 mm
Displacement Volume	1.27 L
Max. power at 6000 rpm	62 kW
Max torque at 4300 rpm	108 Nm

To load the engine and reach the speeds of 1500 to 6000 rpm, with an increment rate of 1500 rpm, an eddy current dynamometer (Apicom model FR100, Italy) with the capability of measuring power up to 100 kW and torque up to 450 Nm was used (Figure 1). The measurement accuracy of power and torque of this dynamometer was 0.1 kW and 1 Nm, respectively, while the measurement accuracy of rotational speed was 1 rpm. The dynamometer was connected to the engine crankshaft via a special rubber coupling.

The rotational speed of the engine as well as the values of power and torque at each speed were visible on the remote control display. The required torque for loads was predetermined and obtained by measuring the maximum torque of the engine. Torque is defined as the rotational effort and is caused by a force that is applied perpendicularly to a distance. The torque of an engine indicates its ability to perform a certain task. Torque essentially determines the ability of a vehicle to move on the desired surface powered by the engine. The torque present in the flywheel of the engine (T) was calculated by:

$$T = R \times F \quad (1)$$

F is the resultant of the forces from combustion and the inertia of the engine's moving parts measured in N, and R is the distance from the center of the crankshaft measured in meters. Power (P) is defined as the work done per unit time and is calculated from equation (2).

$$P = \frac{2\pi TN}{60} \quad (2)$$

N is the speed of the engine in rpm.

Figure 1. Apicom FR100 dynamometer

The engine was placed inside a standard room, which is illustrated in Figure (2). The minimum dimensions of the room are determined based on the principle that no part of the engine should come into contact with the walls of the room.

Figure 2. The PIAGGIO four-cylinder petrol engine and the dynamometer in a standard test room

To measure the exhaust gas temperature, a thermometer (Brannan model HGA4, UK) was used, capable of measuring temperatures from -10°C to 50°C with an accuracy of one degree Celsius, and with a probe length of 150 mm, as shown in Figure (3). The data storage was done in a data acquisition system.

Figure 3. Thermometer used for measuring the temperature of the exhaust gas emissions

The impact of independent variables on the measured variables was evaluated through multiple linear regression analysis using the SAS software. The linear model refers to an equation that is linear concerning its coefficients. Based on this definition, polynomials are classified under linear equations. The multiple regression model has the following general form:

$$y = X\beta + \varepsilon \quad (3)$$

In this relation, y is an n*1 vector of observations, X is an n*p matrix of the model's independent variables, β is a p*1 vector of coefficients, and ε is an n*1 vector of errors.

To evaluate the effects of the engine load and speed on the output power and torque, a two-way ANOVA was carried out. This method was chosen to assess not only the individual effects of load and speed but also their interaction effects on engine performance. The statistical analysis was performed using the following model:

$$Y = C(\text{Load}) + C(\text{Speed}) + C(\text{Load}) : C(\text{Speed}) + \varepsilon \quad (4)$$

Y represents the dependent variable (power and torque), C(Load) denotes the categorical variable for load conditions (25%, 50%, 75%, 100%), C(Speed) represents the categorical variable for engine speed (1500, 3000, 4500, 6000 rpm), and C(Load):C(Speed) corresponds to the interaction effect between load and speed. The residual term ε accounts for unexplained variations in the data.

A factorial ANOVA was used instead of a one-way ANOVA because it allows for the examination of multiple independent variables simultaneously and determines whether the effect of one factor (load) depends on another factor (speed). The analysis was conducted separately for power and torque, ensuring a comprehensive evaluation of the engine performance.

The results of the two-way ANOVA were interpreted based on the F-statistic and corresponding p-values. Statistical significance was set at $p < 0.05$. If the p-value for a factor was below this threshold, it indicated that the factor had a significant effect on the dependent variable. Additionally, an interaction effect with a $p<0.05$ suggested that the influence of load on power and torque varied depending on the engine speed.

A three-way ANOVA was also conducted to evaluate the interaction effects of the engine load, speed, and fuel type on power and torque using the following model:

$$Y = C(\text{Load}) + C(\text{Speed}) + C(\text{Fuel Type}) + C(\text{Load}) : C(\text{Speed}) + C(\text{Load}) : C(\text{Fuel Type}) + C(\text{Speed}) : C(\text{Fuel Type}) + C(\text{Load}) : C(\text{Speed}) : C(\text{Fuel Type}) + \varepsilon \quad (5)$$

Where, C(Fuel Type) accounts for the categorical variable representing different fuel types (Gasoline, CNG, LPG) and the interaction terms was shown similar to Eq. 4. This section of statistical analysis was performed using Python (Statsmodels library), and the results were visualized through boxplots with statistical significance markers (a, b, c, d) to indicate differences between groups. Python was chosen due to its efficiency, automation, and flexibility in handling large datasets and performing statistical computations with high precision. The Statsmodels library enables easy implementation of ANOVA, providing a structured approach to examine the impact of independent variables on dependent variables. The inclusion of interaction terms in the model allowed for a more precise understanding of how gaseous fuels (CNG, LPG) perform compared to gasoline under varying operating conditions.

The data was first structured appropriately, ensuring that all categorical variables were converted into factorized formats. The pandas library was used to clean, reshape, and organize the dataset before running the statistical tests. The melt function in pandas was particularly useful in converting the dataset into a long format, which is essential for conducting factorial ANOVA in Python.

The statistical model was implemented using the Ordinary Least Squares (OLS) regression from the Statsmodels library, which provides a framework for running ANOVA tests efficiently. Python's automation capabilities enabled rapid computation of the sum of squares (SS), degrees of freedom (df), F-values, and p-values, allowing for an accurate determination of statistical significance. The p-values were extracted directly from the ANOVA table, confirming the effects of fuel load and speed on engine performance.

Results and discussion

The different sections of Figure (4) show the output power values of the engine for various fuels at different speeds and loads. As indicated in the figure, the regression analysis shows a significant linear increase at 1% level ($p < 0.01$) in the engine power with increasing speed across various loads, with a high coefficient of determination. In all cases, the highest recorded power is at a speed of 6000 rpm, and the lowest power relates to a speed of 1500 rpm, which could be attributed to the increase in ignition strokes per unit of time (Seifi et al., 2016). Additionally, with an increase in engine loading, its output power also increased. Greater fuel supplement to the engine with increasing its load leads to the stronger combustion, greater mechanical efficiency, and higher output power. A notable point in sections a to c of Figure (4) is the lack of a notable difference in the engine's output power when using three fuels, indicating its ability to operate well with gaseous fuels similar to gasoline. At loadings of 25% and 75% with the speed of 6000 rpm, the output power of gasoline fuel is somewhat less than that of gas ones. Although in a study by Yaliwal et al. a decrease in power for gaseous fuels was observed due to lower volumetric efficiency, the reason for the higher power for gas fuels compared to gasoline in this study may be the need for a longer ignition delay for the evaporation and combustion of gasoline compared to gas fuels, which practically does not have enough time at high engine speeds. Therefore, it can be concluded that in cases where the full power and speed of the engine are not needed for a task (e.g. in transportation), one can safely use gaseous fuels instead of gasoline and even benefit from better output compared to gasoline (Yaliwal et al., 2014). On the other hand, Nutu et al. reported the greatest cylinder pressure and the highest pressure increase in a dual-fuel engine when using LPG (Nutu et al., 2017). Additionally, Mohsen et al. reported a reduction in the ignition delay when using LPG compared to the fossil fuel (Mohsen et al., 2023).

At full load of the engine, where the maximum amount of fuel is injected into the cylinders, the problem of ignition delay for gasoline was solved, and it showed more power than gaseous fuels at all speeds. No difference was observed between the power values obtained for CNG and LPG in sections A to C of Figure (4). LPG has better output than CNG at full load; so that the output power of LPG is equal to that of gasoline at 4500 rpm.

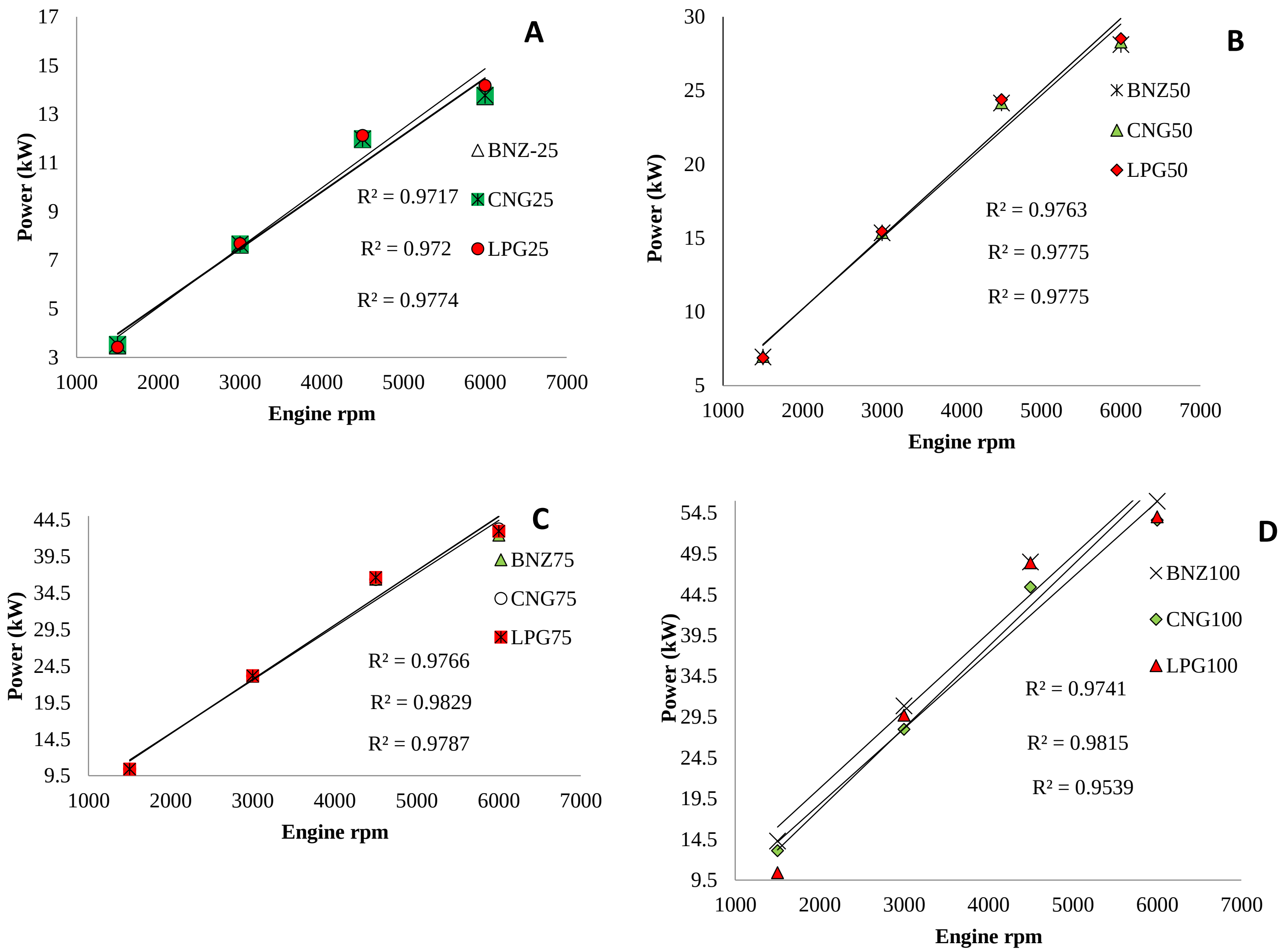

Figure 4. Output power of the engine at different speeds using three studied fuels at loadings: A) 25%, b) 50%, C) 75%, and D) 100%

The ANOVA results confirmed that both engine speed and load had a highly significant effect ($p < 0.001$) on torque and power. Moreover, the interaction effect ($p < 0.001$) was also significant, indicating that the impact of load on engine performance was influenced by the operating speed. These findings justified the use of a factorial ANOVA rather than separate one-way ANOVAs, as they provided deeper insights into how engine load and speed interact to affect torque and power output.

Table 3. Two-way ANOVA results

	Sum_sq	df	F	PR(>F)
C(Fuel)	33368.92	2	46.25872	5.83E-09
C(Load)	193588	4	134.1838	4.72E-16
C(rpm)	842481.9	3	778.6115	4.91E-24
C(Fuel):C(Load)	1291.101	8	0.447458	0.88013
C(Fuel):C(RPM)	621.3004	6	0.287099	0.93732
C(Load):C(RPM)	22837.06	12	5.276433	0.000268
Residual	8656.249	24		

Figure 5 shows that the output power increases significantly as the engine load rises. The alphabetic markers (a, b, c, d) denote statistically significant differences between load conditions ($p < 0.01$). A notable observation is that the difference in power between 75% and 100% load is smaller compared to the lower ones. This suggests that at near-maximum loads, engine efficiency and combustion limitations may play a role in moderating the power gains.

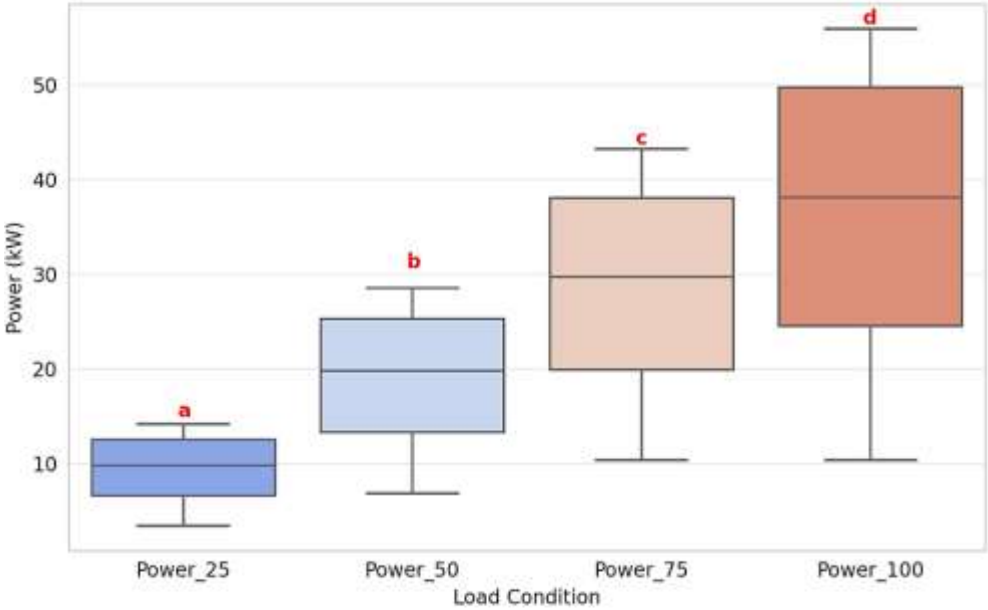

Figure 5. Boxplot of engine power at different load conditions. Significant differences ($p < 0.01$) are marked with different letters. Power output increases with load, but the difference between 75% and 100% is less pronounced.

Figure (6) shows the output torque values of the engine for different fuels at various speeds and loadings. Regression analysis indicates a quadratic relationship between engine torque and speed for different fuels and loadings with a high coefficient of determination. The variations in torque at different speeds and loadings of the engine were significant at the 1% level ($p < 0.01$). As the engine speed increases, the output torque initially increases and then exhibits a decreasing trend.

The reason for the reduction in torque with increasing rpm is the engine's inability to fully supply the cylinder with air, which reduces the combustion efficiency (Abu-Zaid, 2004). Wargula et al. also reported a similar trend for torque at different speeds for gasoline and CNG (Warguła et al., 2020).

The comparison of different sections of Figure (5) also shows the increase in the output torque with an increase in its loading for various fuels. Given the increase in fuel injected into the cylinder, enhancing the output torque for higher loadings is evident. Comparing sections B and C of the figure reveals that at load levels of 50% and 75% with the speeds of 4500 rpm and 6000 rpm, CNG and LPG fuels shows highest output torque and perform better than gasoline. Therefore, it can be confidently said that these two fuels can be used for various tasks when full load is not required. However, as shown in Figure 4 at full load, excessive gasoline injection is associated with a higher output torque for this fuel. Similar behavior observed for the power and torque generated for LPG at full load and a speed of 4500 rpm. Overall, the relative advantage of LPG, with around 102 Newton-meters of torque, which is close to the maximum torque of this engine, is evident compared to CNG. Moreover, the difference in the engine output torque at full load and at speeds below 6000 rpm for the two gas fuels is much more pronounced than partial loads. However, if the engine is supposed to be used at full load and maximum speed, the same torque output can be expected for gas fuels.

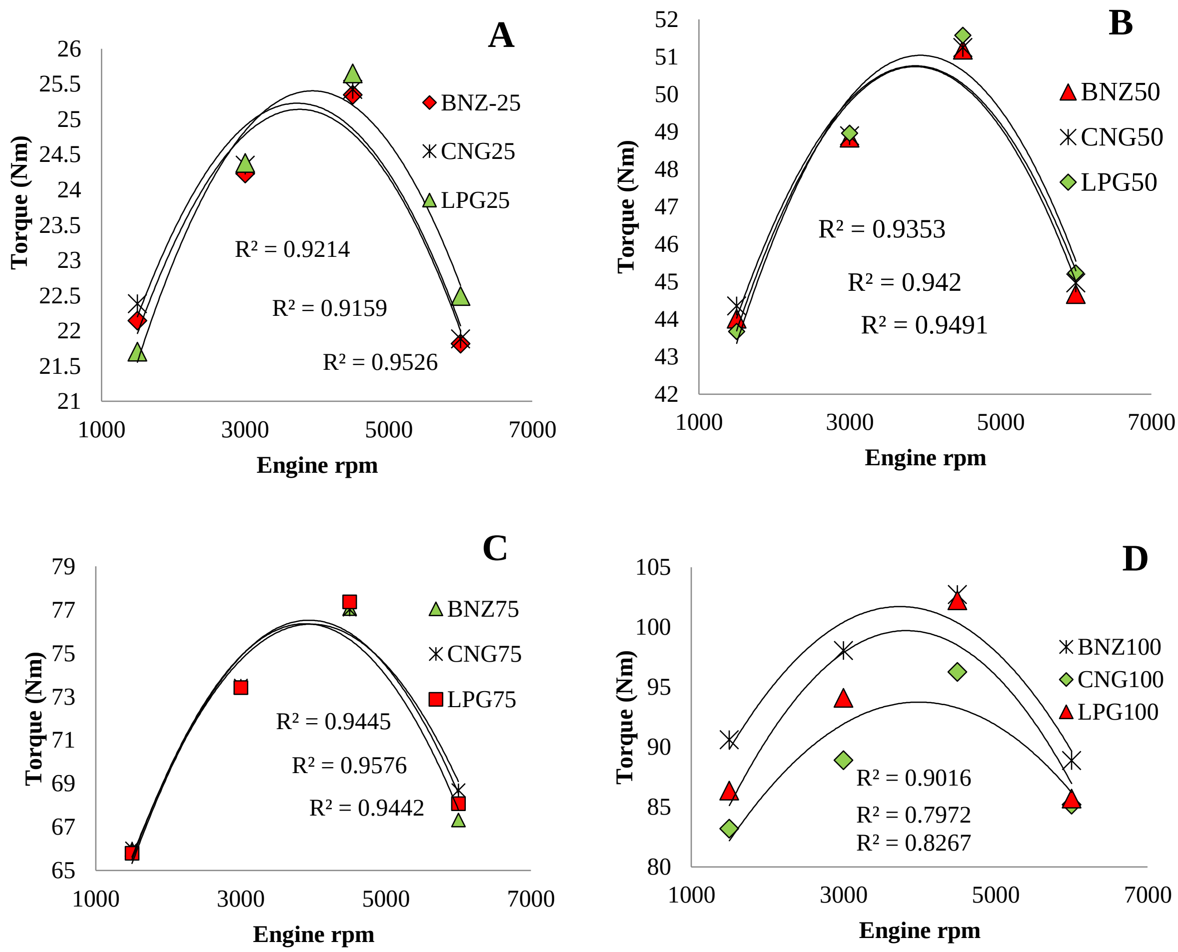

Figure 6. The engine torque at different speeds using three studied fuels at loadings: A) 25%, B) 50%, C) 75%, and D) 100%.

Figure (7) illustrates the torque variations of the engine across different load conditions (25%, 50%, 75%, and 100%). The results demonstrate a clear increasing trend, where torque rises as the engine load increases. The boxplots display the distribution of torque values at each load level, while the statistical significance of differences is indicated using alphabetic markers (a, b, c, d). These markers follow standard statistical conventions, meaning that groups labeled with different letters are significantly different ($p < 0.01$).

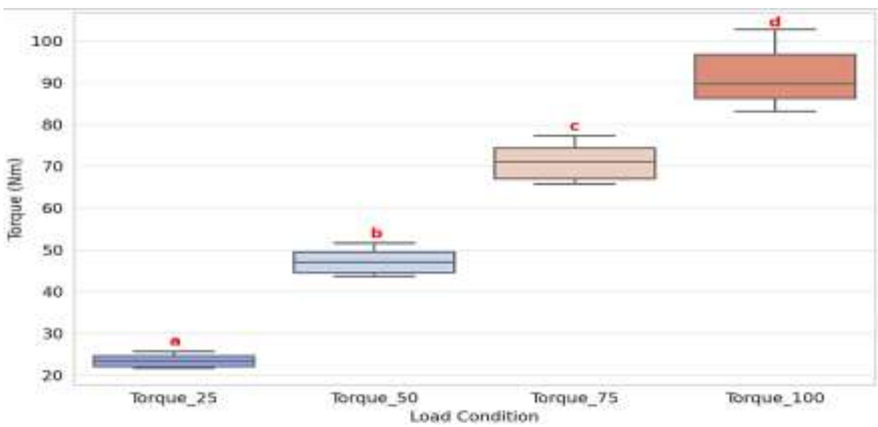

Figure 7. Boxplot of engine torque at different load conditions. Different letters (a, b, c, d) indicate statistically significant differences ($p < 0.01$). Higher loads significantly increase torque, with 100% load showing the highest output.

Table 2 shows the maximum torque values at different loads. Similar to the results obtained from Figure 5, the superiority of gasoline and LPG at full load compared to CNG is quite evident. According to the results of this table, using CNG for tasks that could be done at partial loads does not pose a problem.

Table 2. The maximum torque values at different loading conditions.

Fuel	25%	50%	75%	100%
Gasoline	25.34	51.20	77.06	102.72
CNG	25.42	51.25	77.02	95.27
LPG	25.65	51.57	77.37	102.24

The results of a three-way ANOVA to evaluate the effects of engine load, speed, and fuel type on power and torque output were depicted in Table 3. The analysis included both main effects, which measure the independent influence of each factor, and interaction effects, which assess whether the effect of one factor depends on another or not. The results confirmed that engine load and speed are the dominant factors affecting torque and power, while fuel type does not significantly impact these parameters when considered independently. These findings suggest that CNG and LPG can be used in internal combustion engines without significant losses in performance.

Similar interaction effects were obtained for power and torque. The load-speed interaction was highly significant ($p < 0.001$), indicating that the effect of load is dependent on engine speed. A weak but statistically significant interaction was observed between load and fuel type ($p = 0.005$), suggesting that the power and torque outputs may vary slightly between different fuels under different loading conditions. However, the interaction between speed and fuel type was not significant, meaning that fuel type does not influence how they changes as engine speed increases.

Table 3. Three-way ANOVA results.

	Sum_sq	df	F	PR(>F)
C(Load)	31484.99	3	18986.49	1.10E-31
C(Speed)	631.0169	3	380.5241	1.83E-16
C(Fuel_Type)	18.25084	2	16.50879	8.47E-05
C(Load):C(Speed)	127.7287	9	25.67488	1.72E-08
C(Load):C(Fuel_Type)	71.67489	6	21.61116	2.59E-07
C(Speed):C(Fuel_Type)	5.894281	6	1.777223	0.160634
Residual	9.949703	18		

Figure 8 shows the exhaust gas temperatures at different engine speeds. The results showed an increase in in the exhaust gas temperatures of the engine with increasing speed. More combustion strokes per unit time at higher engine speed is the main factor contributing to the rise of the exhaust gas temperatures.

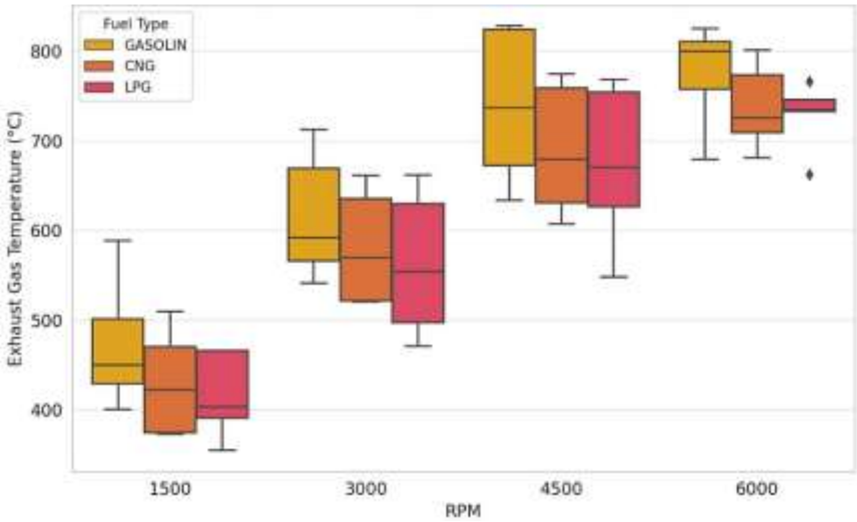

Figure 8. Exhaust gas temperatures of the engine at different speeds.

Figure 9 shows the exhaust gas temperatures at different loads using gasoline, LPG and CNG. Greater temperatures were obtained for higher loading. Zhu et al. reported an increase in the exhaust gas temperature with the torque increment, which has a direct relationship with increasing loading (Zhu et al., 2023). The rise in exhaust gas temperature for higher loading may be due to increased thermal efficiency (Acevedo-Gamboa & Flórez-Serrano, 2012). According to the opinion of these researchers, a small amount of fuel enters the cylinder at low engine load conditions. On the other hand, the cylinder exchanges heat with the surrounding environment through its walls, which can affect the reduction of combustion temperature and thermal efficiency. At high loads, the amount of fuel entering the cylinder significantly increases with the same heat loss from the walls of the cylinder. Therefore, improving the thermal efficiency of combustion with increasing load could be expected. Mohsen et al. also reported an increase in the thermal efficiency when increasing the engine loading for a diesel and LPG fuel mixtures. From this figure it could be observed that the temperature values for CNG and LPG is almost the same (Mohsen et al., 2023). Napoliatano et al. also reported similar reactivity of soot from exhaust gases for LPG and CNG. The differences between no-load (idle) and 25% load, was lower than other loading conditions. This may indicate that operating at zero load is associated with incomplete combustion and engine knocking (Napolitano et al., 2020). The phenomenon of knocking leads to increased pressure fluctuations in the combustion chamber, overheating, and poor engine performance (Sivabalakrishnan & Jegadheesan, 2014). Highest temperature values were obtained for gasoline. It could be due to higher energy content per unit volume of gasoline (34 MJ/L at 250 bar) when compared to CNG (9 MJ/L) (Liu et al., 2021). Another drawback of CNG is its lower flame speed that results in weaker combustion especially at higher speeds. Moreover, it has low volumetric efficiency and energy density (Tabar et al., 2017).

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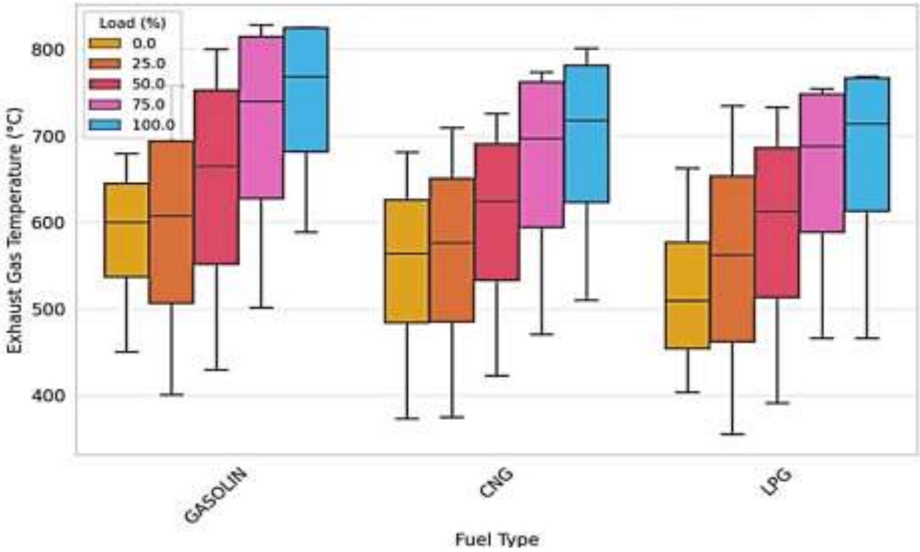

Figure 9. Exhaust gas temperatures of the engine at different loads using the three fuels

Figure 10 shows the interaction between engine load and rpm. It demonstrated that increasing rpm raises the exhaust gas temperature, with a more noticeable effect at high loads (75% and 100%). At loads below 50%, variations in engine speed had a limited impact on temperature. Also, it is observed that the difference between the recorded exhaust gas temperatures at 75% and 100 % loading conditions is smaller than other ones. Furthermore, higher speeds and loads showed almost similar temperatures. Considering the high exhaust gas temperature as an indicative of the having more complete combustion and increased thermal output, 4500 rpm could be identified as the optimal engine speed, as it exhibited the comparable exhaust temperature at high loads. At 6000 rpm, the decrease in exhaust gas temperature suggested limitations in combustion efficiency at excessively high speeds.

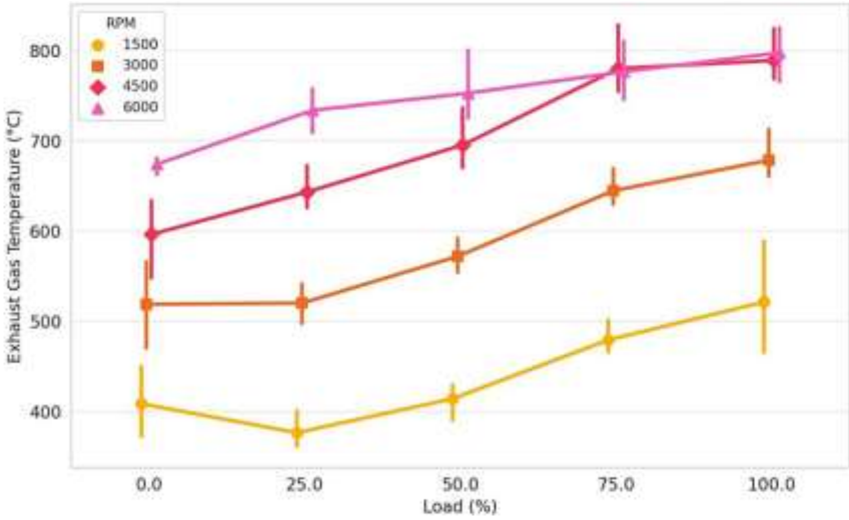

Figure 10. Exhaust gas temperatures of the engine at different loads using the three fuels

CONCLUSION

The increase in the engine speed and loading is accompanied by an increase in output power and the temperature of exhaust gases. There was little difference in the engine's output power when using different fuels at the studied operating speeds. Therefore, gaseous fuels could be safely used instead of gasoline. With increasing speed, the engine's torque initially increases and then shows a decreasing trend. However, the increasing trend of torque was observed with the increase in loading. The results showed comparable output torque for CNG and LPG to gasoline. LPG showed greater torque than CNG. It was observed that the temperature values for CNG and LPG are almost the same. At high loads and speeds, almost similar values for exhaust gas temperature are recorded, which showed efficient combustion at 4500 rpm with minimum heat and friction loss from the cylinder wall. The similarities obtained for exhaust gas temperatures of CNG and LPG as well as the high output torque for LPG suggested this fuel as a good alternative of gasoline without the need for modifications to the engine structure. Considering the points mentioned in the article regarding the changes in combustion temperature using gaseous fuels, it is suggested to test the engine durability with the three types of fuels used in this study. Furthermore, studying the variations in fuel consumption and emissions of the engine is also of special importance and is recommended for future studies.

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