

RESEARCH ARTICLE

Effects of Gasoline and LPG on the Performance and Emissions of a Turbocharged Direct-Injection Vehicle: A Response Surface Methodology Approach

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ABSTRACT – This study aims to investigate the performance and emission characteristics of advanced liquid-phase Liquefied Petroleum Gas (LPG) injection systems retrofitted to gasoline engines. In experiments, a four-stroke, four-cylinder, direct-injection system turbocharged gasoline vehicle was driven on a dynamometer, and wheel power values were measured at different gear intervals and speeds. Additionally, Carbon monoxide (CO), Carbon dioxide (CO₂), Hydrocarbons (HC), Oxygen (O₂), and lambda values were measured using an exhaust emission device. In this study, the results obtained from vehicle tests using LPG and gasoline fuels were investigated by response surface methodology. The input factors for the Response Surface Methodology were determined to be speed and gear spacing, and the response values were determined to be wheel power, CO, CO₂, HC, O₂, and lambda values. As a result, when examining the power values, it is observed that during operation in LPG mode, the 2nd, 3rd, 4th, and 5th gears exhibit increases of approximately 2.94%, 2.38%, 1.85%, and 13%, respectively, compared to operation in gasoline mode. Conversely, during operation in gasoline mode, the 6th and 7th gears show increases of approximately 1.03% and 1.07%, respectively, compared to operation on LPG. When the exhaust emission values are examined, it is determined that the vehicle emits more ideal emissions when operating in LPG mode compared to gasoline mode and meets the standards. Future work should investigate the thermodynamic and combustion characteristics of liquid LPG under varying engine loads and ambient conditions. Advanced modeling techniques, such as machine learning-assisted optimization and real-time control algorithms, could enhance fuel efficiency and emission control. Additionally, system integration studies and component-level durability analyses will be essential for commercialization.

ARTICLE HISTORYReceived : 08th Dec. 2024Revised : 10th July 2025Accepted : 07th Aug. 2025Published : 15th Nov. 2025**KEYWORDS***Direct injection**Exhaust emission**Liquid LPG**Response surface methodology**Vehicle performance*

1. INTRODUCTION

For more than a hundred years, petroleum-based fuels have been the primary energy source for automobile engines operating on the Otto and Diesel cycles. It can be said that the continuation of civilization is closely linked to transportation and the availability of cheap, clean, and stable fuel supplies. Alternative fuels must be evaluated in terms of resource availability, safety, health risks, vehicle performance and emissions, and storage [1]. Studies have shown that energy consumption significantly impacts pollution, public health, and the environment [2]. The internal combustion engine has proven to be a mature and efficient power source across various transportation and industrial sectors [3]. Conventional fuels naturally contain elemental components such as hydrogen, carbon, sulfur, nitrogen, oxygen, and trace metals [4]. Today, the risk of fossil fuel depletion and the rapid increase in emissions have led to a rise in global warming and acid rain incidents [5]. The presence of organosulfur compounds in crude oil significantly contributes to environmental issues, producing combustion by-products such as sulfur oxides (SO_x), including sulfur dioxide and sulfur trioxide [6]. Alternative fuels play a crucial role in addressing the challenges associated with energy production and environmental sustainability. As traditional fossil fuel reserves are rapidly depleting due to increasing energy demand [7], the importance of alternative fuels becomes even more evident. These fuels offer cleaner and more sustainable energy options, which are essential for reducing greenhouse gas emissions and mitigating climate change [8]. Liquefied Petroleum Gas (LPG) is recognized as a fuel with lower carbon dioxide (CO₂) and particulate emissions compared to conventional gasoline or diesel, making it a promising alternative for reducing greenhouse gas emissions [9–11].

To achieve a reduction in greenhouse gas emissions of 15% by 2025 and 30% by 2030, manufacturers bear significant responsibilities [12]. Additionally, the use of alternative fuels can enhance energy security by diversifying energy sources and reducing dependence on imported oil and gas [13]. In recent years, Liquefied Petroleum Gas (LPG) has emerged as a viable alternative fuel for use in spark-ignition engines. LPG is produced as a by-product during the petroleum refining process and is rich in propane, isobutane, butane, and n-butane [14–15].

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The use of LPG is promoted in several European countries. With the legalization and regulation of LPG-powered vehicles, safety has been ensured through appropriate controls, and the use of LPG has steadily increased [16]. The rapid development of the automotive sector and the growing focus on alternative energy sources have accelerated the search for cleaner fuels. Recently, LPG has become more suitable as an alternative fuel in internal combustion engines due to its wide availability, cost-effectiveness, lower exhaust emissions compared to conventional fuels, and higher-octane rating. In many developed countries, including Italy, France, Japan, Belgium, the Netherlands, and the United States, LPG is widely used in automobiles as an alternative fuel. Its adoption is also growing in other countries over time [17]. Alternative fuels in petrol engines are typically used to reduce fuel costs and minimize pollutant emissions in exhaust gases. However, it is equally important that the alternative fuel does not negatively affect vehicle performance, create storage challenges in terms of volume and weight, or compromise safety [18]. LPG-powered vehicles can operate either solely on LPG (dedicated vehicles) or switch between LPG and conventional fuels like gasoline (bi-fuel vehicles) [19, 20]. The production capacity and cost of alternative fuels are also key considerations. In this context, LPG offers several advantages over gasoline when used in spark-ignition engines [21]. Gasoline is less economical and has higher exhaust emission values compared to LPG. To comply with European emission standards, three-way catalytic converters are required, which increase vehicle costs and may pose operational challenges.

As a result, the automotive sector is increasingly focused on developing engines compatible with alternative fuels to reduce exhaust emissions. Another advantage of LPG is that engine oil lasts longer, as combustion results in fewer acids and carbon residues. Since oil contamination and degradation contribute to cylinder wear, the cleaner operation of LPG engines contributes to longer engine life. In terms of exhaust emissions, LPG is considered a cleaner fuel. Carbon monoxide (CO) emissions are significantly lower than those of gasoline, while hydrocarbons (HC) and carbon dioxide (CO₂) also show moderate reductions. Due to the absence of sulfur in LPG, no sulfur oxides (SO_x) emissions are produced. Additionally, black carbon and particulate matter emissions are virtually eliminated [22]. Beyond the differences in fuels and performance modifications, variations also exist in LPG fuel system designs. These are generally categorized into homogeneous and stratified (gradual) filling systems. In homogeneous filling systems, the air-fuel mixture is prepared in the intake manifold and drawn into the engine. The key feature is maintaining a stoichiometric and homogeneous mixture throughout the cylinder. Most modern gasoline engines are designed to operate using homogeneous filling methods [23]. LPG conversion systems for spark-ignition engines have evolved significantly alongside internal combustion engine technology, enabling more efficient use of LPG as a fuel [24]. These systems can be classified as follows:

- Carbureted Engines (First-Generation LPG Systems): Include a mechanical mixing unit for air-fuel mixture preparation.
- SPI (Single Point Injection) Engines (Second-Generation LPG Systems): Feature closed-loop systems with automatic mixture adjustment and an oxygen sensor, compliant with Euro I–II standards.
- MPI (Multi-Point Injection) Engines (Third-Generation LPG Systems): Use closed-loop, multi-point fuel injection with group or sequential injection, meeting Euro II–III norms.
- Sequential Injection (SI) Engines (Fourth-Generation LPG Systems): Feature closed-loop, sequential, and multi-point gas injection systems compliant with Euro III–IV standards [23–26].

Table 1 presents a comparative analysis of LPG and gasoline as engine fuels. In most combustion processes, the required oxygen is supplied by atmospheric air. By volume, atmospheric air consists of approximately 78.09% nitrogen, 20.95% oxygen, 0.93% argon, and 0.03% carbon dioxide. However, in combustion calculations, carbon dioxide and argon are typically neglected, and air is assumed to consist of 79% nitrogen and 21% oxygen by volume. Based on this simplified composition, the molecular weight of air is calculated as 28.851, and there are approximately 3.76 moles of nitrogen for every 1 mole of oxygen [27].

Table 1. Comparison of LPG and gasoline in engine fuel applications [28]

Feature	Fuels		
	Gasoline	Propane	Butane
Stoichiometric Air / Fuel Ratio	16.1/1	15.1/1	15/1
Physical State Under Standard Conditions	Liquid	Gas	Gas
Density at 15 °C (kg/L)	0.73-0.78	0.508	0.584
Lower Thermal Value (MJ / kg)	44	46,4	45.6
Evaporation Concealed Temperature (Kj / kg)	300	426	385
Boiling Point	30-225	-42	- 0.5
Research Octane Number (RON)	96-98	111	103
Motor Octane Number (MON)	85-87	97	89

The literature includes both theoretical and experimental studies on the use of LPG in vehicles. Aydın (2006) [29] conducted experiments on a Hyundai Accent 1.5 GLS vehicle equipped with a Multi-Point Injection (MPI) fuel system and a Lovato brand sequential gas phase LPG injection system. Emission and power values were measured while operating the vehicle on both LPG and unleaded gasoline. The results showed no performance loss and a 40% fuel cost saving when using LPG. Masi and Gobbato (2012) [30] modified a spark ignition engine for dual fuel operation by adding

a second evaporator. Their study found a 4% power reduction when running on LPG compared to gasoline. They also observed that excessive heating in the secondary evaporator negatively impacted engine performance. In another study, Özertaş (2014) [31] tested various mixtures of LPG and hydrogen 100% LPG, 98% LPG + 2% H₂, 96% LPG + 4% H₂, and 94% LPG + 6% H₂ under different cycles at constant excess air coefficients. The findings showed that increasing hydrogen content led to reduced engine performance, but improvements were observed in CO and CO₂ emissions, whereas NO_x emissions increased. Öner (2014) [18] investigated how engine performance and cycle variability were affected by different LPG temperatures. It was found that increased LPG temperature, particularly under high engine loads, reduced effective engine power by approximately 1.90%, and the indicated mean effective pressure dropped by about 1.92%. CO emissions remained nearly constant with increasing LPG temperature, while HC emissions increased slightly, particularly when the LPG regulator outlet temperature exceeded 40 °C. Changes in CO, HC, and CO₂ emissions were minimal; however, NO emissions increased significantly by around 7%. Desrial and Garcia (2018) [32] examined a dual-fuel system (diesel + LPG) on a single cylinder, 8 HP, water-cooled diesel engine. Using Computational Fluid Dynamics (CFD), they simulated LPG-air mixture behavior in the intake manifold. Performance tests were conducted by supplying 20%–40% LPG through the intake air. The optimal performance was observed at a 30% LPG + 70% diesel mixture.

Statistical experimental design is widely applied across various scientific and engineering disciplines [33]. One of the most commonly used techniques is Response Surface Methodology (RSM), a mathematical and statistical approach for modeling and analyzing the effects of multiple variables. RSM allows for the development of statistical models that can predict responses and identify optimal input (control) conditions [34]. As a result, it serves as a powerful tool for process optimization [35]. Moreover, RSM holds potential for enabling real-time monitoring systems in LPG-powered vehicles [36–39]. Its primary objective is to determine the optimal combination of input factors that maximizes or minimizes a target response [40–42]. Optimization studies often use RSM-based algorithms to identify optimal outputs under specific operating conditions [43, 44]. These algorithms utilize mathematical techniques to locate optimum values, and RSM is frequently preferred in engineering applications due to its low error rates [45]. In addition to improving existing systems, RSM also provides a valuable framework for designing new systems [46].

Current advancements in internal combustion gasoline engines are primarily focused on improving performance, reducing emissions, and lowering fuel consumption. In parallel, LPG system manufacturers continue to update their technologies. Given increasingly stringent global exhaust emission standards, the only LPG system suitable for modern gasoline vehicles, including those with direct injection, turbocharging, and multi-point injection, is the liquid-phase LPG system. A dynamometer test can be used to determine engine performance, the power transmitted through the drivetrain, and the actual power delivered to the wheels under simulated road conditions via a computerized testing platform. The experimental design for such tests is typically structured according to the DIN 70020 standard. The innovative aspect of this study lies in the fact that, to date, no research in the literature has investigated the use of liquid phase LPG in vehicles using Response Surface Methodology (RSM).

2. METHODS AND MATERIAL

In parallel with advancements in internal combustion engine technology, LPG systems used in vehicles are continuously evolving to prevent engine power loss and ensure compliance with updated emission standards, such as Euro VI. The most recent development in LPG technology is the liquid phase LPG system, which closely mirrors the original gasoline injection system of the vehicle. This system makes maximum use of the vehicle's existing electronic components, ensuring that the driving experience remains virtually identical between gasoline and LPG operation. As a result, there is no noticeable difference in vehicle performance when running on LPG, and engine output remains equivalent to that of gasoline. Unlike traditional gas-phase systems, the liquid LPG system uses the existing gasoline injectors for LPG delivery. This eliminates the need to drill into the intake manifold, thereby preventing any performance degradation. LPG injection timing is synchronized with that of gasoline and is programmed directly into the vehicle's ECU mapping. Another advantage of this system is that LPG is used from the first engine start, eliminating the need for gasoline during ignition. This allows the vehicle to run on 100% LPG at all times, maximizing fuel savings. In direct injection vehicles, the system uses the original fuel injectors along with a modified high-pressure pump to inject liquid LPG directly into the combustion chamber. Because of this, the vehicle's intake manifold remains intact.

Maintenance intervals are also improved. While older LPG systems require maintenance every 10,000 km, vehicles equipped with the liquid LPG system require servicing only every 25,000 km. A circuit diagram of the system is provided in Figure 1 [47, 48]. The key advantages of the liquid LPG system can be summarized as follows:

- Utilizes innovative, patented Liquid Autogas Injection technology.
- Reduces fuel costs by approximately 50% compared to gasoline.
- Produces lower CO₂ emissions, contributing to environmental protection.
- Maintains excellent drivability as engine control is managed by the vehicle's original ECU.
- Operates exclusively on LPG from start-up, eliminating the need for gasoline.
- Requires less frequent maintenance.
- Engine power and performance remain unaffected.
- Uses the vehicle's original fuel system components, avoiding intrusive modifications.

- Unaffected by variations in autogas composition, ambient temperature, humidity, or altitude.
- All components are certified in accordance with ECE R 67-01 standards [49].

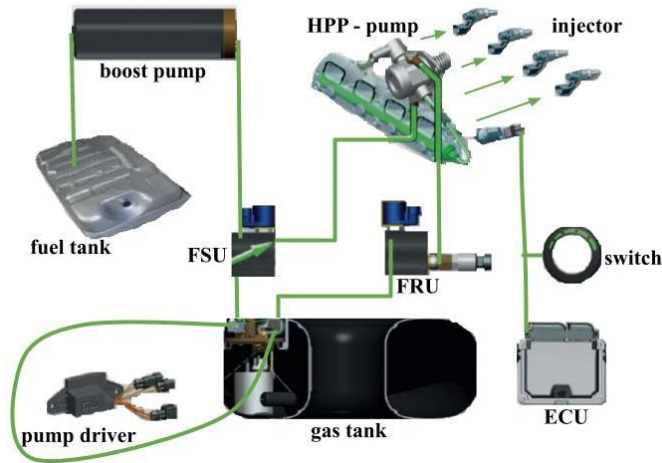


Figure 1. DLM system diagram

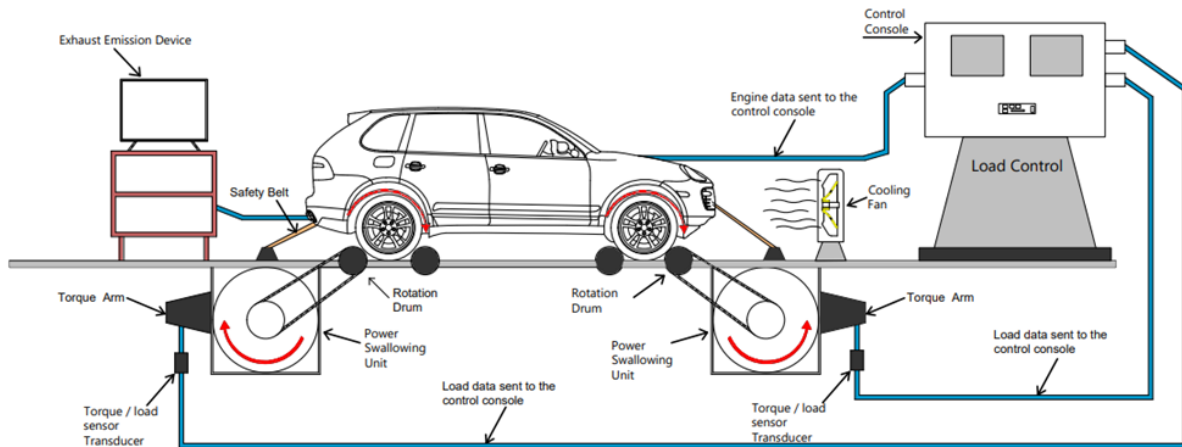


Figure 2. Test set-up

2.1 Test Vehicle Mounted Liquid LPG

Experiments were conducted on a 2016 model Hyundai Tucson equipped with a 1.6-liter turbocharged direct injection engine, fitted with a Prins brand liquid LPG system. The technical specifications of the test vehicle are presented in Table 2, and the experimental test setup is illustrated in Figure 2.

Table 2. Technical Specifications of the test vehicle [50, 51]

Trademark	Hyundai
Version Name	Tucson 1.6 T-GDI DCT 4x4
Category	SUV
Engine Type	Turbo GDI
Fuel Injection Type	Direct Injection
Engine Capacity (cc)	1591
Max. Speed (km/h)	201
Max. Power Output (HP)	177 / 5500 min ⁻¹
Max. Torque (Nm)	265 / 4500 min ⁻¹
Operating Principle	4 strokes
Number of Cylinders	4
Number of Valves	16 Valve DOHC
Cooling Type	Water Cooled
Gearbox (Gearbox)	DCT 7-speed
Tires - front and rear	245/45R19

2.2 Dynamometer Used in the Tests

In the experiments, a DYNOBIL XR 4WD-600 vehicle dynamometer was used. This type of dynamometer is capable of measuring wheel and engine power and torque, engine RPM, vehicle speed, engine traction, and performing speedometer tests as well as road simulations [52].

2.3 Exhaust Emission Device Used in Experiments

In the experiments, a BILSA MOD 2210 exhaust emission analyzer was used, with its technical specifications provided in Table 3. To ensure measurement accuracy, the device's filters were replaced prior to testing. A visual representation of the BILSA MOD 2210 device is shown in Figure 3.

Table 3. Technical parameters of the exhaust gas emission measurement device [53]

Parameters	Measurement Range	Measurement Precision
CO (%)	0-10	%0.001
CO ₂ (%)	0-20	%0.001
HC (ppm)	0-10000	1 ppm
O ₂ (%)	0-25	%0.01
CO Corr. (%)	0-10	%0.001
Lambda	0.5-2	0.001
AFR	5-30	
Speed (rpm)	0-9990 d/d	10 d/d
K (Dimming coefficient)	0-9.99	0.01m ⁻¹
Operating ambient	0°C+40°C	% 0.01



Figure 3. BILSA MOD 2210 brand exhaust emission device

Unleaded gasoline and LPG were used as fuels in the vehicle experiments. The test vehicle was a 2016 model 4x4 Hyundai Tucson 1.6 TGDI, equipped with a Prins-brand liquid LPG system and powered by a four-stroke, four-cylinder, turbocharged gasoline engine with direct injection. The vehicle was tested on a dynamometer, where wheel power values were measured at various gear ratios and vehicle speeds. Additionally, CO and CO₂ emissions were recorded using an exhaust emission analyzer. Throughout the tests, full synthetic CASTROL 5W-30 engine oil was used to ensure consistent engine lubrication.

2.4 Response Surface Methodology

Response Surface Methodology (RSM) is an experimental design technique that utilizes statistical and mathematical methods to examine the effects of input factors on response variables, with the aim of reducing the number of required experiments and optimizing results. Through this approach, the relationship between input factors and response values can be represented by a mathematical prediction function. If the response variable is found to have a statistically significant linear relationship with the input factors, the predictive function is defined as a first-order model. This model is expressed by Eq. (1), which includes the constant coefficient (β), the number of input factors (k), the input variables (X), and the standard error (ϵ) [54]. For systems where the relationship between variables cannot be adequately explained by a linear function, a second-order (quadratic) model is used. This more complex model is given in Eq. (2) and includes linear and polynomial coefficients (i and j , respectively) to account for curvature in the response surface [55].

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_k X_k + \epsilon \dots \tag{1}$$

$$y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum \sum_{i<j}^k \beta_{ij} X_i X_j + \epsilon \dots \tag{2}$$

Experiments in RSM-based designs can be structured using various techniques [56, 57]. In this study, a total of 3^k test combinations were generated using the three-level full factorial design (3LFD) technique, where k represents the number of input factors. This technique was selected because it allows for the evaluation of input factors at low, medium, and high levels, providing a comprehensive understanding of their effects on the responses. The prediction functions derived from the 3LFD approach enable response estimation using actual (real-world) input values. The results of the ANOVA analysis for gasoline fuel are presented in Table 4, and those for LPG fuel are shown in Table 5. The input factor levels, based on vehicle speed ranges corresponding to different gear positions, are listed in Table 6.

The following variables were determined as response values:

- Wheel power (kW)
- Carbon monoxide (CO, % vol)
- Carbon dioxide (CO₂, % vol)
- Hydrocarbons (HC, ppm)
- Oxygen (O₂, % vol)
- Lambda (λ)

Table 4. ANOVA analysis for gasoline fuel

Factors	Power (kW)		λ		CO (%)		CO ₂ (%)		HC (ppm)		O ₂ (%)	
	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value
A: Gear	134.95	0.0000	163.28	0.0000	197.22	0.0000	45.92	0.0000	24.10	0.0004	0.48	0.5032
B: Velocity	1.48	0.2465	0.01	0.9408	13.73	0.0030	2.15	0.1682	2.35	0.1516	5.33	0.0395
A ²	0.49	0.4963	82.03	0.0000	128.11	0.0000	19.12	0.0009	63.24	0.0000	3.79	0.0753
AB	0.29	0.6024	0.18	0.6804	34.67	0.0001	3.27	0.0955	7.30	0.0192	0.41	0.5327
B ²	0.01	0.9390	0.12	0.7321	4.58	0.0537	0.43	0.5222	0.03	0.8765	0.12	0.7324
R ²	91.58		95.34		96.92		85.52		88.99		85.79	
MAE	9.5162		0.0056		0.0006		0.1329		4.8469		0.0138	

Table 5. ANOVA analysis for LPG fuel

Factors	Power (kW)		λ		CO (%)		CO ₂ (%)		HC (ppm)		O ₂ (%)	
	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value	F-Ratio	P-Value
A: Gear	99.19	0.0000	11.34	0.0056	215.16	0.0000	70.15	0.0000	24.04	0.0004	0.05	0.0190
B: Velocity	1.83	0.2011	0.41	0.5333	13.03	0.0036	3.02	0.1079	2.41	0.1462	2.81	0.1192
A ²	1.39	0.2606	0.25	0.6250	130.44	0.0000	26.04	0.0003	61.23	0.0000	9.75	0.0088
AB	0.27	0.6149	4.66	0.0517	38.31	0.0000	5.08	0.0436	6.84	0.0226	0.24	0.6322
B ²	0.00	0.9470	0.10	0.7629	0.35	0.5626	0.09	0.7637	0.03	0.8606	0.74	0.4061
R ²	89.53		88.27		97.06		89.68		88.73		88.12	
MAE	6.62321		0.0064		0.0007		0.1254		4.8993		0.01238	

Table 6. Speed ranges according to gear positions

Gear Position	Level	Speed (km/h)	Gear Position	Level	Speed (km/h)
2.th	1	40	5.th	1	100
	2	50		2	110
	3	60		3	120
3.th	1	60	6.th	1	120
	2	70		2	130
	3	80		3	140
4.th	1	80	7.th	1	140
	2	90		2	150
	3	100		3	160

3. RESULTS AND DISCUSSION

In this study, power parameters were measured in accordance with DIN 70020 standards, while exhaust emission values were obtained following ISO 3930 standards. Based on the experimental measurements, the characteristic performance curves of the vehicle were generated.

3.1 Wheel Power

Figure 4 presents the wheel power values measured at various vehicle speeds and gear positions, ranging from second to seventh gear. In second gear, the maximum wheel power using LPG fuel was measured at 35 kW at 60 km/h, representing a 2.94% increase compared to gasoline. In third gear, LPG achieved a maximum power of 43 kW at 80 km/h, corresponding to a 2.38% improvement over gasoline. In fourth gear, LPG yielded a maximum wheel power of 55 kW at 100 km/h, indicating a 1.85% increase compared to gasoline. In fifth gear, the maximum power reached with LPG was 95 kW at 120 km/h, marking a significant 13% increase over gasoline. Conversely, in sixth gear, gasoline produced a higher maximum wheel power of 98 kW at 140 km/h, which is a 1.03% increase compared to LPG. Similarly, in seventh gear, gasoline resulted in a maximum wheel power of 94 kW at 140 km/h, representing a 1.07% increase over LPG.

$$\text{Gasoline WP} = -2,54444 + 19,1774 * GP + 7,03333 * SR - 0,565476 * GP^2 - 0,771429 * GP * SR - 0,333333 * SR^2 \tag{3}$$

$$\text{LPG WP} = -5,95556 + 22,8762 * GP + 5,5 * SR - 1,09524 * GP^2 - 0,857143 * GP * SR + 0,333333 * SR^2 \tag{4}$$

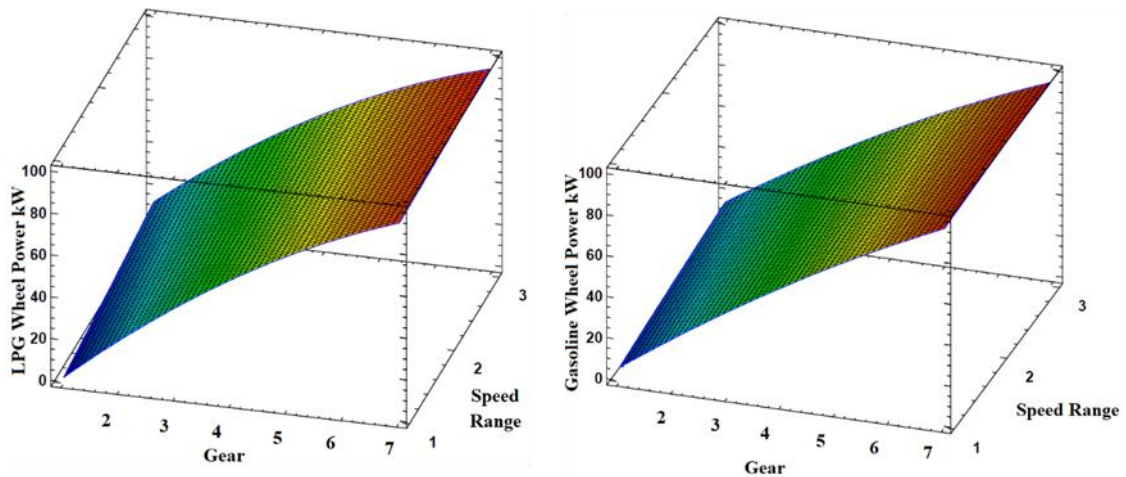


Figure 4. Wheel power values at different vehicle speeds

3.2 Carbon Monoxide Emissions

The CO emission values measured at different vehicle speeds and gear positions (from second to seventh gear) are presented in Figure 5. In second gear at 60 km/h, under gasoline mode, the CO emission at maximum power was 8.57% higher than that in LPG mode. In third gear at 80 km/h, the CO emission under gasoline mode was 9.37% higher compared to LPG. In fourth gear at 100 km/h, a 5.71% increase in CO emissions was observed with gasoline compared to LPG. In fifth gear at 120 km/h, gasoline mode produced 5.12% higher CO emissions than LPG. In sixth gear at 140 km/h, CO emissions under gasoline mode were 6.66% higher than those with LPG. In seventh gear, also at 140 km/h, a 4.54% increase in CO emissions was recorded with gasoline compared to LPG. These results indicate that LPG fuel consistently produces lower CO emissions than gasoline across all tested gear positions and speeds, particularly under maximum power conditions.

$$\text{Gasoline CO} = 0,0530889 - 0,00822381 * GP - 0,0073 * SR + 0,00116667 * GP^2 + 0,00108571 * GP * SR + 0,00116667 * SR^2 \tag{5}$$

$$\text{LPG CO} = 0,0485444 - 0,00853452 * GP - 0,00426667 * SR + 0,00120833 * GP^2 + 0,00117143 * GP * SR + 0,000333333 * SR^2 \tag{6}$$

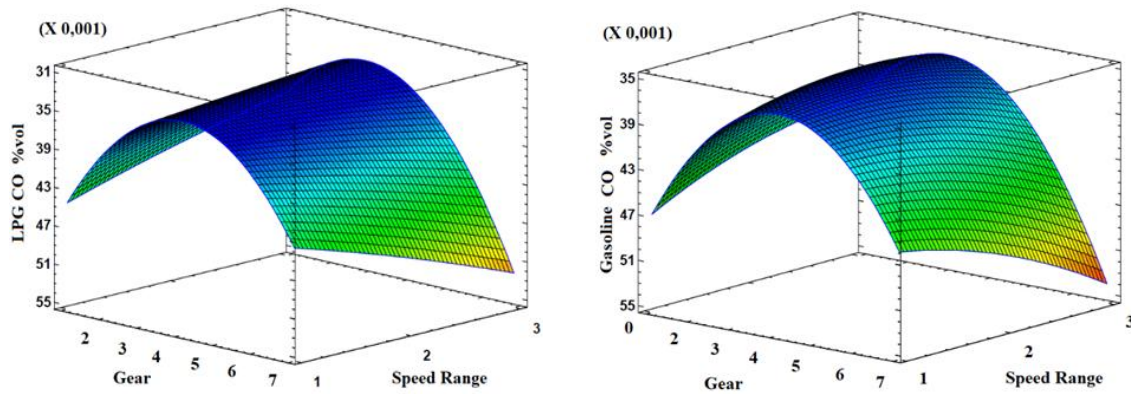


Figure 5. CO emission values at different vehicle speeds

3.3 Carbon Dioxide Emissions

The CO₂ emission values measured at different vehicle speeds and gear positions (from second to seventh gear) are presented in Figure 6. In second gear at 60 km/h, under petrol mode, the CO₂ emission at maximum power was 0.29% higher than in LPG mode. In third gear at 80 km/h, petrol mode showed a 0.28% increase in CO₂ emissions compared to LPG. In fourth gear at 100 km/h, CO₂ emissions under petrol mode were 0.21% higher than LPG. In fifth gear at 120 km/h, a 0.28% increase in CO₂ emissions was observed with petrol compared to LPG. In sixth gear at 140 km/h, petrol mode CO₂ emissions were 0.51% higher than those with LPG. In seventh gear at 140 km/h, petrol mode produced 0.55% more CO₂ emissions than LPG. These results demonstrate that LPG fuel consistently produces slightly lower CO₂ emissions than petrol across all tested gears and speeds, especially at maximum power.

$$Gasoline\ CO_2 = 14,0978 + 0,520733 * GP + 0,3985 * SR - 0,0837619 * GP^2 - 0,062 * GP * SR - 0,0668333 * SR^2 \tag{7}$$

$$LPG\ CO_2 = 14,1121 + 0,568613 * GP + 0,276067 * SR - 0,0919583 * GP^2 - 0,0726857 * GP * SR - 0,0293333 * SR^2 \tag{8}$$

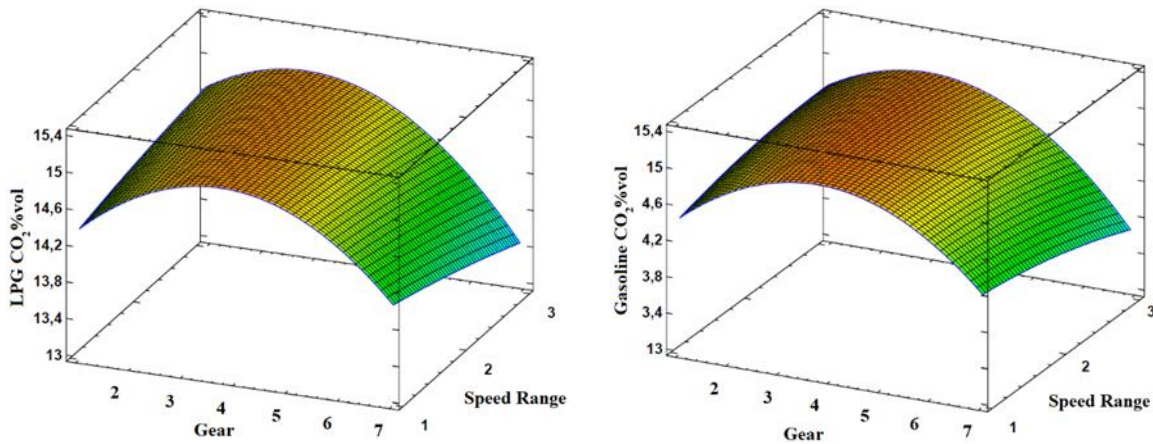


Figure 6. CO₂ emission values at different vehicle speeds

3.4 Hydrocarbon Emissions

The HC (hydrocarbon) emission values measured at different vehicle speeds and gear positions (from second to seventh gear) are shown in Figure 7. In second gear at 60 km/h, under petrol mode, the HC emission at maximum power was 2.5% higher than in LPG mode. In third gear at 80 km/h, a 3.12% increase in HC emissions was observed with petrol compared to LPG. In fourth gear at 100 km/h, HC emissions under petrol mode were 4% higher than LPG. In fifth gear at 120 km/h, petrol mode showed a 4.76% increase in HC emissions compared to LPG. In sixth gear at 140 km/h, HC emissions in petrol mode were 1.81% higher than LPG. In seventh gear at 140 km/h, petrol mode produced 1.53% more HC emissions than LPG. These results indicate that LPG fuel consistently results in lower hydrocarbon emissions than petrol across all tested gears and speeds, particularly at maximum power.

$$Gasoline\ HC = 90,1222 - 40,4 * GP - 6,16667 * SR + 5,52381 * GP^2 + 3,35714 * GP * SR - 0,583333 * SR^2 \tag{9}$$

$$LPG\ HC = 87,6778 - 40,0012 * GP - 5,5 * SR + 5,49405 * GP^2 + 3,28571 * GP * SR - 0,666667 * SR^2 \tag{10}$$

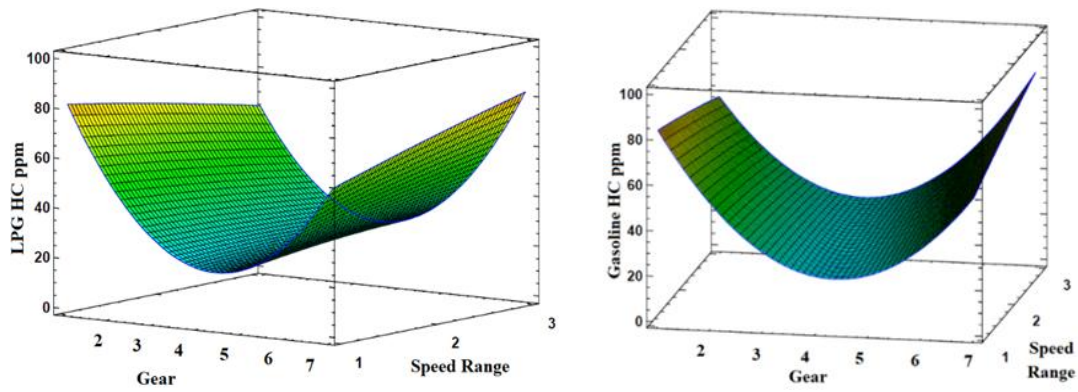


Figure 7. HC emission values at different vehicle speeds

3.5 Oxygen Values

The O₂ (oxygen) emission values measured at different vehicle speeds and gear positions (from second to seventh gear) are presented in Figure 8. In second gear at 60 km/h, under LPG fuel mode, the O₂ value at maximum power was 21.42% higher compared to petrol fuel mode. In third gear at 80 km/h, LPG mode showed a 26.6% increase in O₂ compared to petrol mode. In fourth gear at 100 km/h, O₂ emissions in LPG mode were 9.37% higher than in petrol mode. In fifth gear at 120 km/h, LPG mode had a 20% increase in O₂ emissions compared to petrol mode. In sixth gear at 140 km/h, O₂ emissions were 13.3% higher in LPG mode than petrol mode. In seventh gear at 140 km/h, LPG mode showed a 7.4% increase in O₂ compared to petrol mode. These results indicate that LPG fuel consistently produces higher oxygen levels in the exhaust gases than petrol across all tested gears and speeds at maximum power.

$$\text{Gasoline } O_2 = 0,0338667 + 0,0195024 * GP - 0,00693333 * SR - 0,00367857 * GP^2 + 0,00217143 * GP * SR - 0,0035 * SR^2 \tag{11}$$

$$\text{LPG } O_2 = -0,0409 + 0,0420607 * GP + 0,0284 * SR - 0,00548214 * GP^2 - 0,00154286 * GP * SR - 0,008 * SR^2 \tag{12}$$

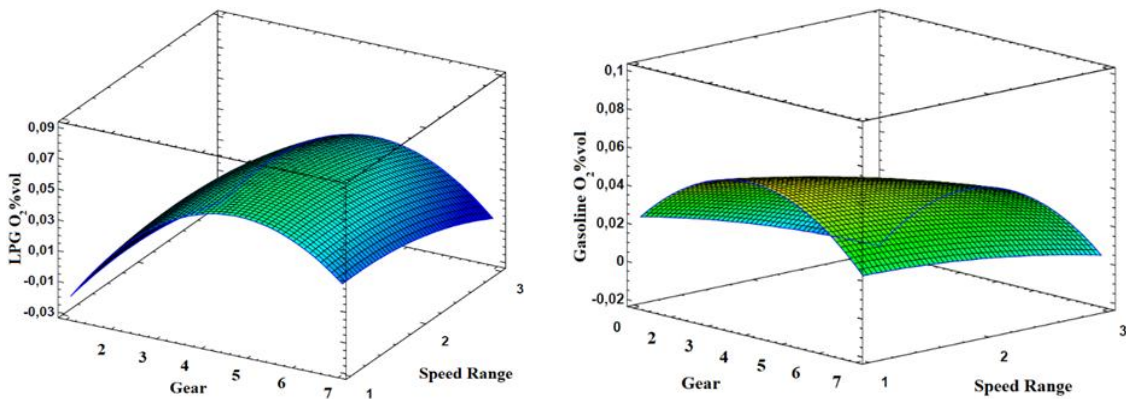


Figure 8. O₂ emission rates at different vehicle speeds

3.6 Lambda Value

The lambda (λ) values measured at different vehicle speeds and gear positions (from second to seventh gear) are presented in Figure 9. In second gear at 60 km/h, under petrol fuel mode, the λ value at maximum power showed a 1.42% increase compared to the LPG fuel mode λ value. In third gear at 80 km/h, petrol mode λ values were 6.59% higher than those of LPG mode at maximum power. In fourth gear at 100 km/h, the petrol fuel λ value increased by 6.88% compared to LPG mode. In fifth gear at 120 km/h, a 6.59% increase in λ value was observed for petrol compared to LPG mode. In sixth gear at 140 km/h, the petrol fuel λ value was 4.92% higher than in LPG mode. In seventh gear at 140 km/h, there was a marginal 0.20% increase in petrol mode λ value compared to LPG. These results indicate that lambda values tend to be higher under petrol fuel mode than LPG across all tested gears and speeds at maximum power, with the difference decreasing at higher gears.

$$\text{Gasoline } \lambda = 1,03649 + 0,0310786 * GP + 0,0036 * SR - 0,0065119 * GP^2 + 0,000542857 * GP * SR - 0,00133333 * SR^2 \tag{13}$$

$$\text{LPG } \lambda = 0,990244 - 0,000716667 * GP + 0,0224667 * SR + 0,000511905 * GP^2 - 0,00394286 * GP * SR - 0,00166667 * SR^2 \tag{14}$$

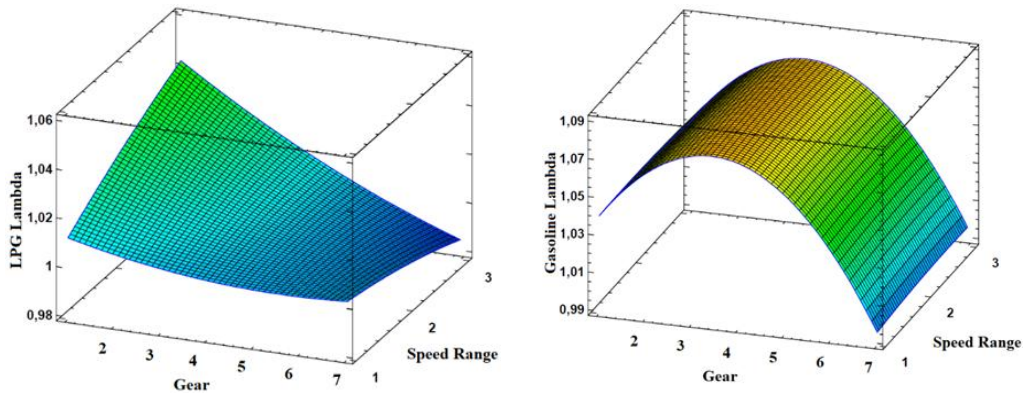


Figure 9. Lambda (λ) values at different vehicle speeds

3.7 Pareto Charts for all Fuels

Figure 10 presents the Pareto charts corresponding to the experimental results obtained using gasoline as fuel. According to the analysis, Factor A has a significant influence on the engine performance and emission characteristics. Specifically, Factor A contributes to a reduction in CO₂ emissions, excess air ratio (lambda), and residual oxygen (O₂) levels in the exhaust gases. Conversely, it leads to an increase in carbon monoxide (CO) and unburned hydrocarbon (HC) emissions, as well as engine power output.

On the other hand, Factor B also affects both emissions and performance parameters, albeit in a different manner. It is observed that Factor B causes a decrease in CO₂ and O₂ levels, while increasing CO, HC, lambda, and engine power. This indicates that Factor B enriches the air-fuel mixture to a certain extent, resulting in incomplete combustion, which explains the elevated CO and HC levels along with a higher lambda value. The increase in power suggests that the combustion process yields higher energy output under the influence of Factor B despite being richer.

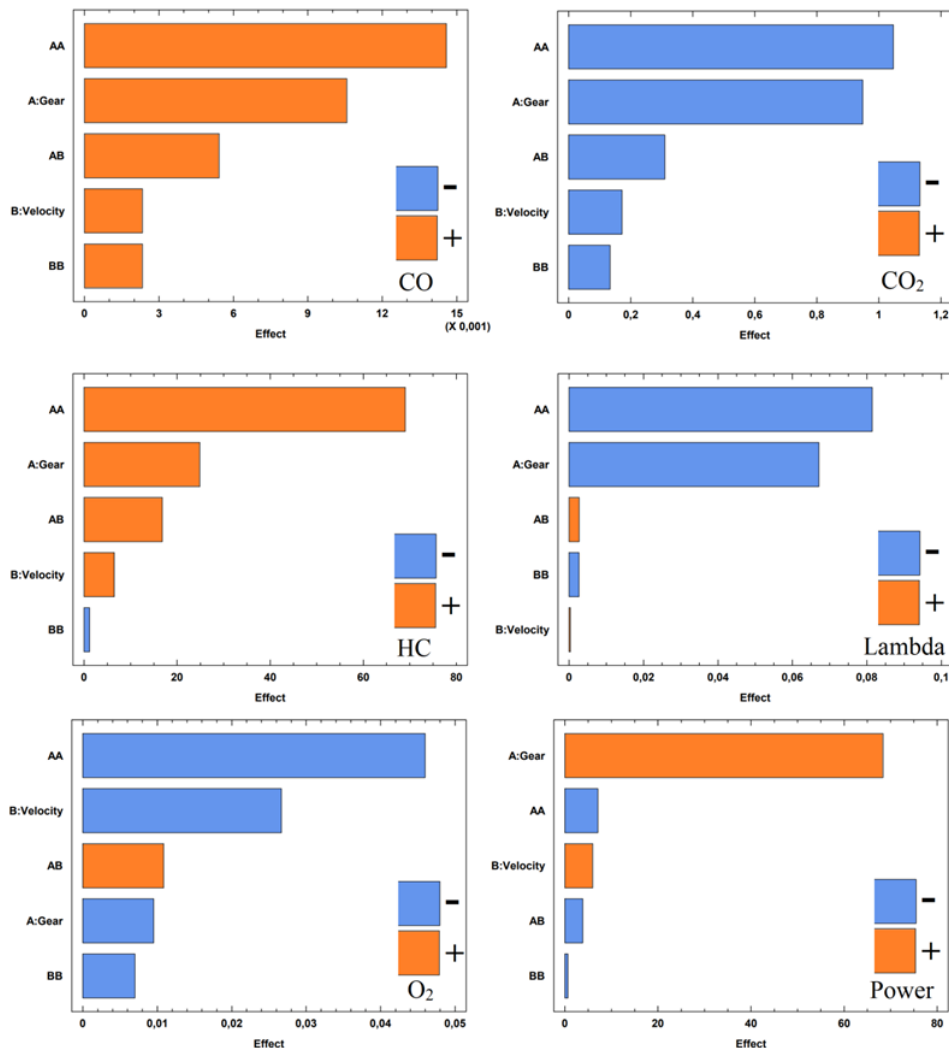


Figure 10. Pareto charts of gasoline fuel for all responses

Figure 11 illustrates the Pareto charts derived from the experimental data using LPG as fuel. The analysis reveals that Factor A has a notable impact on both engine emissions and performance parameters. Specifically, Factor A results in a reduction in carbon dioxide (CO₂) emissions and the air–fuel equivalence ratio (lambda), indicating a shift toward a richer combustion mixture. Simultaneously, Factor A leads to increases in carbon monoxide (CO) and unburned hydrocarbon (HC) emissions, residual oxygen (O₂) in the exhaust, as well as engine power output. The increase in O₂ despite the richer mixture suggests possible combustion inefficiencies or incomplete oxidation.

Similarly, Factor B also influences the combustion and emission characteristics when operating with LPG. Factor B is observed to decrease CO₂ and O₂ concentrations, while increasing CO, HC, lambda, and engine power. The rise in lambda implies a leaner mixture tendency compared to Factor A, yet the concurrent increase in CO and HC emissions points to suboptimal combustion. The enhanced power output under the influence of Factor B indicates that, despite the less efficient combustion, the engine still delivers higher performance.

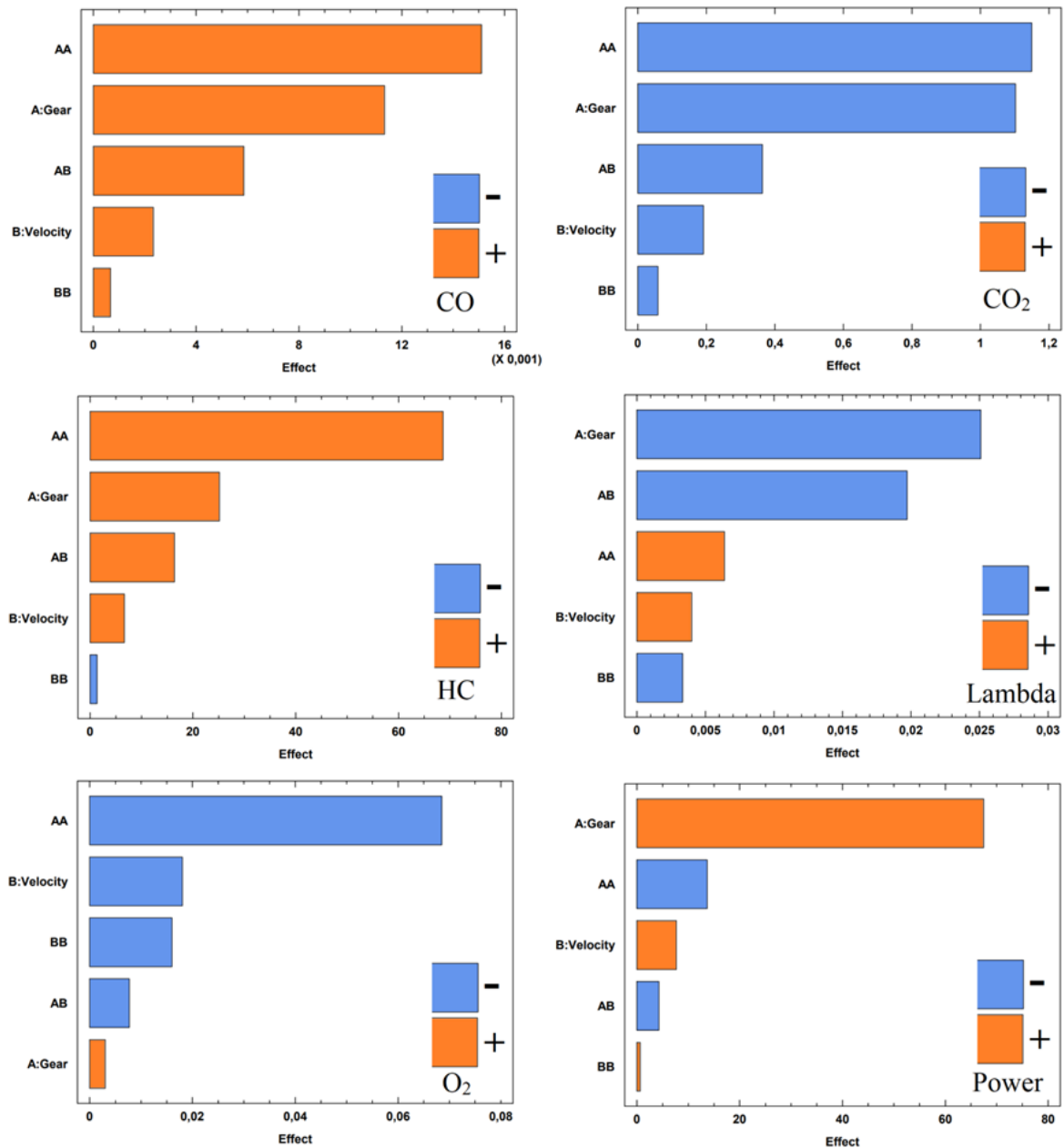


Figure 11. Pareto charts of LPG fuel for all responses

The power output and exhaust emissions, including CO, CO₂, HC, O₂, and lambda (λ), were investigated, and the results obtained showed similarities with those reported by Balki (2005) [58]. According to Balki’s experimental data, operating with LPG resulted in a significant reduction in carbon monoxide (CO) emissions, approximately 80–95% lower compared to gasoline operation. Additionally, hydrocarbon (HC) emissions decreased by an average of about 35–40%. A reduction in CO₂ emissions was also observed during LPG operation, which is attributed to the lower carbon atom content in LPG fuel compared to gasoline. This study, which evaluated changes in emissions and engine power across different gears and speeds, clarified the effects of using LPG and gasoline fuels on emission values and engine

performance. Beyond promoting a more environmentally friendly and conscious driving profile for vehicle operators, this work also provides valuable insights and ideas for future researchers investigating this topic.

4. CONCLUSIONS

This study comprehensively examines the effects of advanced liquid-phase LPG injection systems on vehicle performance and exhaust emissions, in direct comparison to conventional gasoline operation in contemporary spark ignition (SI) engines. Experimental investigations were carried out on a 2016 model Hyundai Tucson 1.6 TGDI, which features a direct-injection, turbocharged gasoline engine architecture. Performance and emission data, including wheel power output and exhaust constituents (CO, CO₂, HC, O₂, and lambda), were collected under both LPG and gasoline fueling modes across multiple gear ratios, using a chassis dynamometer to simulate real-world driving conditions.

The results indicated that the use of LPG did not result in any measurable loss of engine power. On the contrary, marginal increases in wheel power were observed in the mid-range gears (second to fifth), which can be attributed to the favorable combustion characteristics of LPG, such as its higher-octane number and superior knock resistance. However, a slight power reduction was observed in higher gears (notably sixth), likely due to increased pumping losses and mechanical friction at elevated engine speeds and loads.

In terms of exhaust emissions, operation in LPG mode consistently yielded lower CO and HC emissions compared to gasoline. This improvement is primarily due to the more homogeneous air-fuel mixture formation and cleaner combustion behavior associated with gaseous fuel injection. Furthermore, CO₂ emissions were significantly reduced under LPG fueling, attributable to the lower carbon content of LPG fuel (typically composed of approximately 30% propane and 70% butane by volume) relative to gasoline, which has a higher molecular weight and carbon density (C₈H₁₈).

Elevated residual oxygen (O₂) concentrations observed during LPG operation are a result of LPG's lower volumetric energy density, which leads to higher excess air levels under stoichiometric control. Lambda values under LPG operation were observed to be closer to the theoretical stoichiometric value, indicating improved combustion efficiency and more stable air-fuel control.

The implementation of advanced liquid phase LPG injection technology effectively overcomes several of the limitations historically associated with conventional vapor phase LPG systems, particularly in terms of throttle response, mixture formation, and cold start behavior. These advancements suggest that LPG can serve as a viable alternative to gasoline, offering both environmental and performance advantages.

Moreover, the use of Response Surface Methodology (RSM) enabled the development of predictive models to analyze the interactive effects of gear ratio and fuel type on power output and emissions with a reduced number of experimental trials. This statistical approach proved to be an efficient and robust tool for optimizing engine performance and minimizing emissions in dual-fuel configurations. The findings support the broader adoption of LPG as an alternative fuel, especially when complemented by appropriate regulatory incentives and infrastructure development.

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DECLARATION OF COMPETING INTEREST

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

AUTHOR CONTRIBUTIONS

Fatih Aydın: Conceptualization, formal analysis, investigation, methodology, software, supervision, visualization, writing – original draft

İdris Kırmaz: Investigation, supervision, writing – review and editing

DATA AVAILABILITY STATEMENT

Data will be made available on request.

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NOMENCLATURE

%	Percent
λ	lambda
°C	Celsius degree
AC	Alternative current
AFR	Air Fuel Ratio
CFD	Computational Fluid Dynamics
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
DCT	Dual Clutch Transmission
DIN	Deutsches Institut für normung
DLM	Direct Liquimax
DOHC	Double Over Head Cam
GDI	Gasoline Direct Injection
GP	Gear Position
HC	Hydrocarbon
Hz	Hertz
H ₂	Hydrogen
ISO	International Organization for Standardization
LFD	Level factorial design
LPG	Liquefied petroleum gas
MAE	Mean Absolute Error
MON	Motor octane number
MPI	Multi Point Injection
NO	Nitrogen Oxide
O ₂	Oxygen
ppm	Parts per million
RON	Research octane number
RSM	Response Surface Methodology
SO _x	Sulfur oxides
SPI	Single Point Injection
SR	Speed Range
TS	Turkish standard
WP	Wheel Power