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Using the response surface methodology to analyze the effect of fuel injection pressure on lambda, ignition advance and exhaust emissions in the SI engines

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ABSTRACT

In gasoline engines, the fuel delivery system is one of the most precise and critical components. The design of fuel pathways, pumps, filters, and related features directly impacts fuel pressure a key parameter for combustion performance. This study investigates the effect of fuel injection pressure on lambda (the ratio between the actual air-fuel ratio and the stoichiometric air-fuel ratio), ignition advance, and exhaust emissions in a gasoline engine using the response surface methodology (RSM).The test results indicate that lambda, ignition advance, CO, and HC emissions increase with decreasing fuel injection pressure. The highest values of lambda (1.044), ignition advance (37°), and CO (0.88%) were recorded at 5000 rpm with a fuel injection pressure of 2.4 bar. Conversely, the highest CO_2 concentration (14.8%) was observed at 1000 rpm with a fuel injection pressure of 3.5 bar. The lowest HC emission (86 ppm) was reported at 5000 rpm with a fuel injection pressure of 3.5 bar.The findings demonstrate that fuel injection pressure significantly influences engine performance and emissions. Proper design and maintenance of the fuel system to maintain optimal fuel pressure can enhance engine performance and reduce exhaust emissions. This plays a crucial role in mitigating air pollution, particularly in metropolitan areas.

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Introduction

Nowadays, one of the most important problems of big cities is the increase of air pollution, so the governments are trying to make laws to reduce these pollutants. One of the main topics of these laws is to control and reduce air pollution in big cities and greenhouse gases from the activities of large factories and exhaust emissions of cars, heavy industrial and agricultural machines with gasoline and diesel engines. Also, exhaust from gasoline vehicles plays a major role in air pollution in large cities. Reduction of fossil fuel sources, automotive pollutions, strict regulations and human health problems have led to extensive studies in the field of controlling and reducing pollutants from the exhaust of internal combustion (IC) engines by researchers around the world.

Internal combustion engines are divided into two main groups: spark ignition engines (SI) and compression ignition engines (CI). Internal combustion engines are made up of many parts. The fuel system of gasoline engines is one of the most important and sensitive systems in these engines. The main components of the fuel system include tank, fuel pump, fuel transfer pipes, fuel filter, fuel rail and injectors. The fuel pressure is one of the important parameters in internal combustion engines performance. However, this parameter will be affected by the operation of the engine after a short time, and some factors such as reduced quality of fuel pump performance, deviation in the fuel supply path, clogged gasoline filter due to high lifetime, improper regulator performance and dirty injectors cause a fuel pressure drop in the fuel rail. The correct operation of the fuel system has an effect on improving the quality of combustion, increasing engine efficiency, reducing knocking and exhaust gases. Today, precision in fuel purification is much more important in fuel injection engines than in the old carburetor fuel system. In an injector engine, each injector has one or more small holes less than 0.2 mm in diameter, and each injector opens for less than 0.005 seconds when injecting fuel. Therefore, the presence of foreign particles in the fuel can easily lead to clogging of the injector ducts [1, 2]. In the present world, the need for fossil fuels has greatly increased and with the extraction of petroleum, fossil fuels have decreased and air pollutants have increased [3]. In a study, the maximum outlet pressure of the fuel pump with a filter lifetime of 50,000 km was measured as 4.5 bar. Also, the lowest inlet pressure was measured at 3.5 bar when using a new filter. The results showed that the fuel filter lifetime also has a significant effect on the main parameters of the engine, such as fuel-air mixture weight ratio and the ignition advance. Studies in Euro2 and Euro4 engines have shown that the ignition advance at 1,000 rpm engine speed with a new fuel filter was 7 degrees (minimum value), while the maximum ignition advance at 5,000 rpm engine speed and with a 50,000 km filter lifetime was measured at 37 degrees. The results of another part of the previous research showed that gasoline filter clogging has a significant effect on fuel pressure, fuel-air mixing ratio, and ignition advance, which in turn will have a direct impact on combustion quality and engine thermal efficiency. Therefore, One of the important factors of pressure drop in the fuel rail is the fuel filter lifetime [4]. Based on the importance of fuel injection pressure, Ejtehadi [5] examined important factors in fuel filtration of advanced diesel engines. According to the results obtained in his research, the application of appropriate principles in the preparation, maintenance and distribution of fuel, will significantly improve the performance of these devices and will significantly reduce the cost of repairs. Jafarian Jolodar et al [6] using the (RSM) response surface method, tried to optimize the parameters affecting the production process of gasoline filters by plastic injection method. His results have been useful in optimizing the production of gasoline filters. Contamination from impurities is one of the most common problems with fuels. Contamination in conventional fuels comes from a wide range of sources, such as dust and particles from fuel pump wear in the fuel system [7].

In a study by Kamyab et al [8] focusing on simulating the fluid behavior in the fuel filter and fuel circuit of a helicopter, they concluded that the filter and other device of fuel system used would create a pressure drop in the range of 0 bar to 1 bar due to its cleanliness this disrupts military helicopter missions. Regarding the effect of fuel pressure on the performance of gasoline engines, in a study, the effect of increasing the fuel filter life on fuel feeding and ignition systems was investigated. The results showed that the use of long life fuel filter, especially more than 15,000 km, increases the electric current consumption of the fuel pump, the operating temperature of the pump, the fuel temperature in the fuel feeding system and thus shortening the life of the fuel pump. In the ignition system, with the increase of the gasoline filter life, the amount of ignition advance increased, which can cause complications such as premature combustion, knocking in the engine and reducing the useful life of the main engine parts [9]. The most important emissions in internal combustion engines are carbon monoxide, unburned hydrocarbons and nitrogen oxides, which will increase emissions due to incomplete combustion [10]. Also injector fuel injection pressure plays an important role in increasing the quality of combustion and reducing exhaust emissions. The relationship between fuel flow with performance variables and exhaust emissions was investigated and the results showed that uniform fuel flow has an effect on increasing combustion efficiency and reducing the emission of pollutants from the exhaust of combustion engines [11]. In an experimental study, the effect of designing a new fuel filter called a whale on the emission of pollutants from diesel engine exhaust in four different types of devices was investigated. The results of this study showed that the average levels of carbon monoxide, unburned hydrocarbons and nitrogen oxides decreased by 35.3%, 26.1% and 34.3%, respectively [12]. Sharma and Kumar [13] investigated the effect of fuel pressure and engine speed on parameters such as combustion, performance and emissions of gasoline engines using different fuel compositions.Their results showed that fuel pressure can be an effective variable in engine performance.

In many researches, the response surface method has been used to investigate the performance parameters of internal combustion engines. Almasi et al [14] in a study using the response surface method, investigated the production process of biodiesel from non-edible rapeseed oil. In this research, the response surface method was able to model the reaction efficiency of the biodiesel production reaction from non-edible canola oil with high accuracy using a quadratic polynomial equation. In order to optimize the EGR ratio, Jalilian Tabar et al [15] studied the operating conditions of a diesel engine and the amount of pollutants emitted from the exhaust using the RSM method. Dole et al [16] proposed a mathematical model to investigate the relationship between pollutant emissions and performance parameters of a dual-fuel diesel engine such as engine load, engine speed and the amount of hydrogen-replaced fuel. They used the RSM to evaluate emissions and diesel engine performance. Shabani et al [17] in one study, the performance of a tractor engine was evaluated using a mixture of biodiesel and ethanol fuel by the response surface methodology. According to the results of his research, the rotational speed of the engine was the most effective factor in increasing engine power. In addition, the combination of biofuels, diesel and ethanol and engine speed were the most important indicators of specific fuel consumption. Using the response surface methodology, Erol et al [18] predicted the performance and exhaust emissions of a diesel engine with biodiesel fuel extracted from canola. In another study, different engine variables such as load and fuel composition were predicted to improve the various parameters of a diesel engine using the response level method [19]. Using the response surface methodology, the effect of different alternative fuels on the performance and exhaust emissions of a 6-cylinder diesel engine was investigated [20]. In a study, the effect of injection pressure and injector strategy optimization on improving the performance of an internal combustion engine was evaluated using the response surface methodology [21].

Omi et al [22] in a numerical study using the KIVA-3V simulator program investigated the effect of fuel injection time on the rate of fuel evaporation and emissions in a gasoline engine. The results of his research showed that late spraying of fuel will reduce fuel evaporation. On the other hand, increasing the rate of fuel evaporation reduces CO and HC emission. But to reduce NOx emission, spark time adjustment should be used. In a theoretical study using AVL-Fire software investigated the effect of time and fuel injection pressure on the performance and emissions of the diesel engine. The results of his research showed that increasing fuel injection pressure will increase NOx and decrease PM [23]. A review of previous research shows that there are a lot of researches on reducing exhaust emissions from internal combustion engines by changing the engine design, replacing new parts in different engine systems, using filtration systems in exhaust outlets such as catalysts and changing the type of fuel used. However, the effect of important parameters such as fuel injection pressure on some of the main characteristics of the engine such as engine power, Lambda, ignition advance, combustion quality and the amount of exhaust emissions in the gasoline engine has not been investigated so far. In this study, various engine variables, especially the fuel system, were fully controlled and recorded, but the main purpose of this study was to investigate the effect of fuel injection pressure and engine speed on the lambda, ignition advance and exhaust emissions. For this purpose, the effect of fuel injection pressure and engine speed on the three important exhaust outlets of a gasoline engine (CO, CO2 and HC), stoichiometric ratio (lambda), and ignition advance was investigated and analyzed. The results of this research can be used in the optimal design of the fuel system, fuel filter, fuel pump and other parts of this system in order to establish the maximum appropriate pressure in the fuel rail.

Methodology

Materials and Methods

Test Apparatus

In this research, a Linear four-stroke gasoline engine has been used. The technical specifications of the engine are listed in Table 1. To conduct the experiments, a pressure regulating valve and a pressure gauge were installed upstream of the fuel rail to measure fuel pressure. Based on prior research, a new fuel pump and new fuel filter were employed to ensure maximum pressure in the fuel system.

Exhaust emissions; including carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbons (HC)—were measured using a MAHA MGT5 exhaust gas analyzer (manufactured in Germany). The stoichiometric ratio (lambda, λ) was also recorded using this device. The pressure gauge and gas analyzer are illustrated in Figure 1, and the specifications of the gas analyzer are detailed in Table 2.

Various engine parameters such as engine speed, manifold inlet air pressure, oxygen sensor voltage, ignition advance, injector injection time, throttle angle, stoichiometric ratio and engine cooling temperature were carefully controlled in the laboratory. The experiments were performed at an ambient temperature of 30°C and the laboratory temperature was controlled with an accuracy of 1°C. All measuring equipment is calibrated before use in tests.

Table 1. Main Specifications of the engine used in this research

Characteristic type	SI engine, 4 Cylinder
Company	Saipa Iran
No. of Cylinder	4
Maximum Torque (N.m)	103
Displacement Volume (cc)	1323
Combustion Order	1-3-4-2
Type of ECU	Siemens
Type of fuel system	Single spray injector
Maximum power (hp)	63 hp

a

b

Figure 1. Pressure gauge (b) and the exhaust gas analyzer (a)

Table 2. Specifications of the exhaust gas analyzer

Parameters	Unit	Measurements Range	Measurements Accuracy	Uncertainty
CO	%	0–15% vol.	0.01% vol	± 0.3
CO_2	%	0–20% vol	0.01% vol.	± 0.2
HC	ppm	0–9999 ppm	1 ppm	± 0.2
Lambda	-	0.5–9.99 ppm	0.01	± 0.2

In each stage of the tests, after adjusting the fuel pressure, the engine ran for about a minute, then the engine water temperature was monitored, and when the temperature reached 80 °C , the engine speed was increased under no-load conditions until the target speed was achieved. After stabilizing the engine conditions, the parameters were measured and recorded. A schematic of the experimental setup is provided in Figure 2.

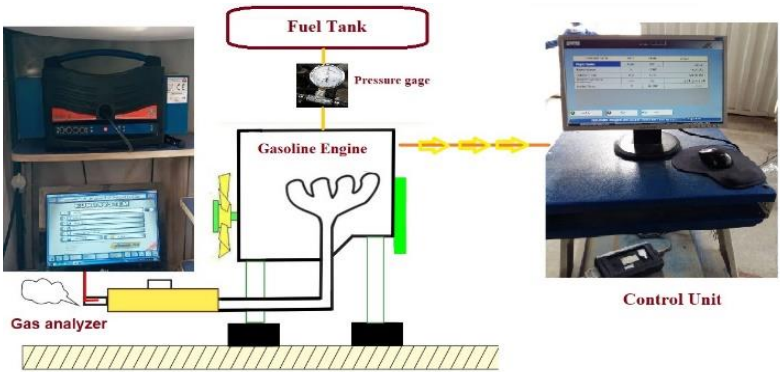


Figure 2. Schematic of experiments and measuring devices

Uncertainty Analysis

The uncertainty for each parameter was analyzed using the square root method [24]. The uncertainty values for individual parameters are listed in Table 2. The overall percentage of uncertainty was calculated using the following equation:

$$\text{Percentage of uncertainty} = \sqrt{(0.3)^2 + (0.2)^2 + (0.2)^2 + (0.2)^2} = \pm 0.21\%$$

where the uncertainties for CO, CO_2, HC, and λ were 0.3%, 0.2%, 0.2%, and 0.2%, respectively.

Design of Experiments

Given the large number of tests, complexity, and high cost associated with engine experiments, a statistical design of experiments (DoE) was employed. The Response Surface Methodology (RSM) was used for statistical analysis, implemented via Design-Expert® Software (version 10).

A central composite design (CCD) was adopted to evaluate the influence of independent variables (fuel injection pressure and engine speed) on dependent variables (ignition advance, λ, and exhaust emissions: CO, CO2, HC). The experimental matrix and factor ranges are summarized in Table 3, and the software-generated experimental design is presented in Table 4.

RSM involves mathematical and statistical techniques for designing experiments, modeling processes, and optimizing responses [25]. The relationship between responses and independent variables is often unknown, so an approximation function is used. If the response is linearly dependent on the variables, the model is expressed as;

First-Order Model (Linear Relationship) [26]:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \epsilon \tag{1}$$

where:

y = response,

β_0 = intercept,

β_i = coefficients,

x_i = independent variables,

ϵ = error term.

If there is curvature in the system, higher order polynomials should be used, such as the second-order model in Equation [2] [27].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \epsilon \tag{2}$$

Table 3. The experiment matrix

Independent variables	Symbols	Limit of each factor
Fuel Pressure (bar)	A	2.4 – 3.5
Engine Speed (Rpm)	B	1000 - 5000

Table 4. Experimental design proposed by RSM

Run	Std	Fuel Pressure (bar)	Rpm	Ignition Advance (Degree)	Lambda	Co (%)	Co2 (%)	HC (ppm)
6	1	3.5	5000	34	1.031	0.82	14.1	88
2	2	2.95	5000	36	1.038	0.85	13.9	101
9	3	2.95	3000	24	1.028	0.74	14.4	117
3	4	2.95	3000	23	1.028	0.75	14.4	117
1	5	2.4	1000	15	1.021	0.72	14.2	215
5	6	2.95	3000	23	1.029	0.74	14.4	117
12	7	3.5	1000	7	1.017	0.55	14.9	196
7	8	2.4	3000	26	1.032	0.78	13.8	125
11	9	2.95	1000	11	1.018	0.61	14.6	205
13	10	2.4	5000	37	1.042	0.88	13	110
4	11	3.5	3000	22	1.022	0.69	14.6	109
8	12	2.95	3000	24	1.028	0.74	14.3	119
10	13	2.95	3000	24	1.028	0.74	14.4	117

Results and discussion

Lambda (stoichiometric ratio)

The ideal ratio of air to fuel (theoretical) can be obtained based on the chemical balance of the gasoline combustion with air. This ideal mass ratio (Air/Gasoline) has a value of 14:1 and is known as the stoichiometric ratio. On the other hand, for ideal stoichiometric ratio, a coefficient called lambda (λ) is defined and calculated by the following equation:

$$\lambda = \frac{(A/F)_{Actual}}{(A/F)_{Theoretical}} \quad (3)$$

Where [28]:

λ < 1: Rich mixture (excess fuel),

λ = 1: Stoichiometric mixture,

λ > 1: Lean mixture (excess air).

Figure 3 shows a three-dimensional diagram of the interaction between fuel injection pressure and engine speed on the stoichiometric ratio. According to the three-dimensional diagram, it can be seen that:

- increasing fuel injection pressure reduces λ, while increasing engine speed raises λ.
- Lower pressure in the fuel rail can reduce fuel atomization, leading to a leaner mixture (higher λ) and poorer combustion quality [4, 29].

According to Figure 3 and the results of Analysis of Variance (ANOVA) in Table 5, confirm that:

- both fuel pressure (A) and engine speed (B) significantly affect λ at the 1% level. Their interaction (AB) is significant at the 5% level.

One of the goals of this research in using the response surface method is to reach an equation that shows the relationship between lambda with fuel pressure and engine speed. The regression equation between the independent variables and the dependent variables is shown in Equation 4, which can also predict and detect different values of variables.

$$\lambda = 1.03 + 0.0043A + 0.0091B - 0.0017AB \quad (4)$$

where:

A = Fuel injection pressure (bar),

B = Engine speed (rpm).

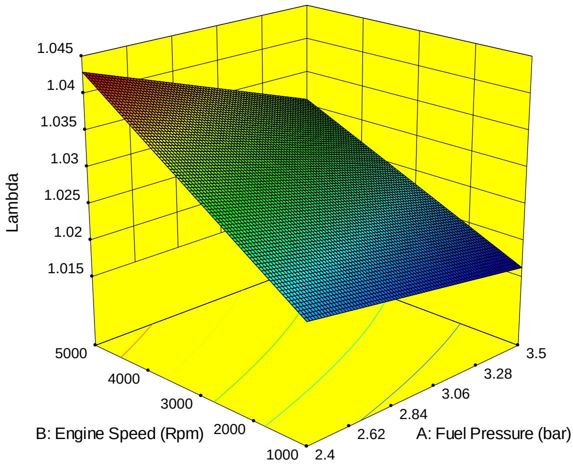
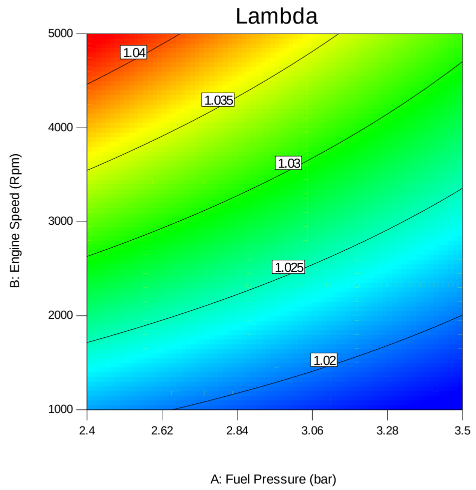


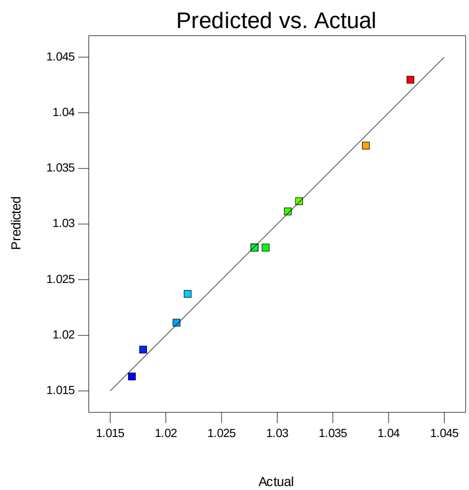
Figure 3: Interaction of fuel pressure and engine speed on lambda

The contour diagram in Figure 4 shows the interaction of fuel pressure and engine speed on the lambda. It is observed that when the fuel pressure is more than 3 bar and the engine speed is less than 1500 rpm, the lambda is less than 1.02.

By examining the diagrams in Figure 4, it can be seen that the results obtained experimentally correspond to the results predicted by the software. Also, the correlation coefficient was R = 0.98, which shows a very good correlation between the predicted results and the actual data. That is, 98% of the dependent variables depend on independent variables, and only 2% of the dependent variables cannot be explained using independent variables, which proves the validity of the model.



A



B

Figure 4: Contour plot (a) Comparison of actual results with the predicted results of lambda (b)

Table 5 presents the results of analysis of variance to evaluate the tested variables. The p-value in the analysis of variance table shows the significant effect of all the independent variables on the dependent variables. P-value <0.05 indicates the significance of the effect of variables on the response. But P-value> 0.1 indicates that the effect of variables on the response is not significant. Also, lower values for P-value indicate more significance, for statistical significance at 95% to 99 confidence levels. The% P-value should be less than 0.05 to 0.01, respectively. According to the results of analysis of variance in Table 5, it can be seen that the model used to investigate the effect of independent variables on dependent variables is significant and it can be predicted using the first-order polynomial equation. Examining the p-value for different sources in Table 5, it can be concluded that the fuel pressure (A), engine speed (B) at the level of 1% and the interaction of fuel pressure and engine speed (AB) have a significant effect on the lambda at the level of 5%. Also, the low number of residuals, Lack of Fit and Pure Error show the validity of the model.

Table 5: Analysis of variance of lambda

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	6.206E-004	3	2.069E-004	261.89	< 0.0001
A-Fuel Pressure	1.042E-004	1	1.042E-004	131.88	< 0.0001
B-Engine Speed	5.042E-004	1	5.042E-004	638.28	< 0.0001
AB	1.225E-005	1	1.225E-005	15.51	0.0034
Residual	7.109E-006	9	7.899E-007		
Lack of Fit	6.309E-006	5	1.262E-006	6.31	0.0493
Pure Error	8.000E-007	4	2.000E-007		
Cor Total	6.277E-004	12			

Ignition Advance

Figure 5 shows the interaction between fuel injection pressure and engine speed on changes in Ignition Advance. According to the three-dimensional diagram, as fuel injection pressure and engine speed increase, ignition advance decreases and increases, respectively. Because changing the weight of stoichiometric ratio from the ideal state will lead to a change in ignition advance [4 and 29]. According to Figure 5 and the results of analysis of variance in Table 6, it is clear that the two variables of fuel injection pressure and engine speed and interaction of fuel injection pressure and engine speed have a significant effect on ignition advance at the level of 1%, respectively. The regression equation between independent variables and dependent variables is shown in Equation 5, which can also predict and detect different values of variables. In this equation, A is the fuel injection pressure (bar) and B is engine speed (Rpm).

$$\text{Ignition Advance} = 23.54 - 2.50\,A + 12.33\,B + 1.25\,AB \quad (5)$$

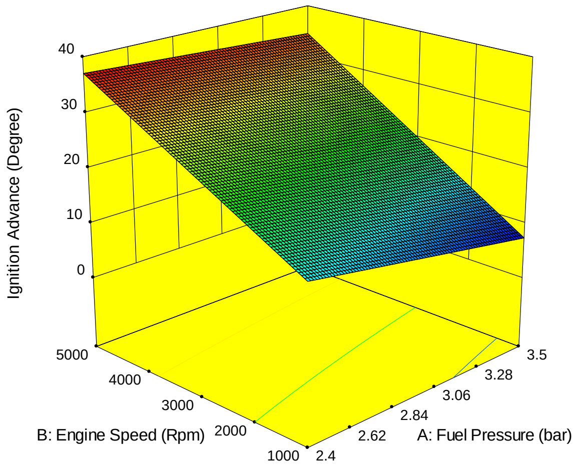
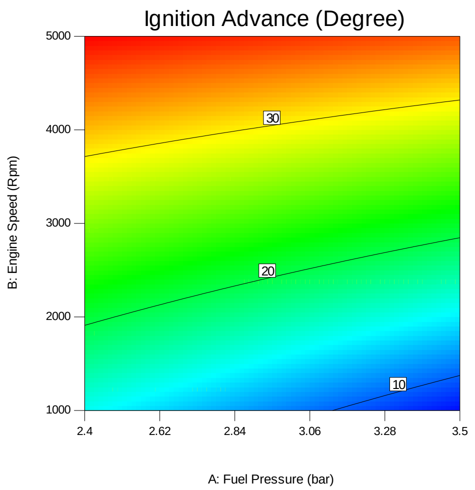


Figure 5: Interaction of fuel pressure and engine speed on ignition advance

By Looking at Contour plot (Figure 6) , it is confirmed that that ignition advance decreases with rising fuel pressure and ANOVA (Table 6) shows fuel pressure (A), engine speed (B), and their interaction (AB) are significant at the 1% level. Also R^2 = 0.99 validates the model's predictive accuracy.



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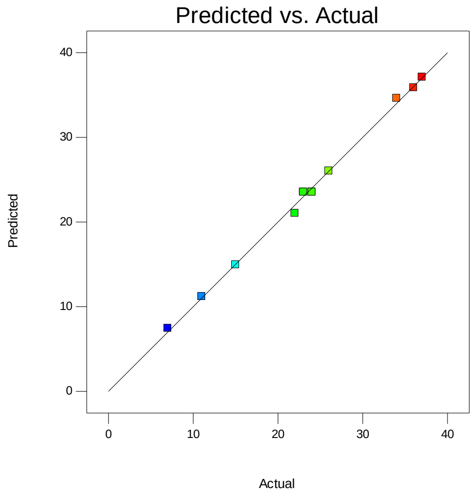


B

Figure 6: Contour plot (a) Comparison of actual results with the predicted results of ignition advance (b)

Table 6: Analysis of variance of Ignition advance

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	956.42	3	318.81	1019.60	< 0.0001
A-Fuel Pressure	37.50	1	37.50	119.93	< 0.0001
B-Engine Speed	912.67	1	912.67	2918.87	< 0.0001
AB	6.25	1	6.25	19.99	0.0016
Residual	2.81	9	0.31		
Lack of Fit	1.61	5	0.32	1.08	0.4852
Pure Error	1.20	4	0.30		
Cor Total	959.23	12			

CO emission

Figure 7 illustrates the impact of fuel pressure and engine speed on carbon monoxide (CO) emissions. The increase in CO emissions is attributed to elevated Lambda (λ), poor air-fuel mixture quality, and reduced combustion efficiency [30].

According to Figure 7 and the results of analysis of variance in Table 7, it is clear that the two variables of fuel pressure and engine speed have a significant effect on CO emission at the level of 1%, respectively. The regression equation between independent variables and dependent variables is shown in Equation 6, which can also predict and detect different values of variables. In this equation, A is the amount of fuel pressure (bar) and B is engine speed (Rpm).

$$CO = 0.74 - 0.053\,A + 0.11\,B + 0.028\,AB \quad (6)$$

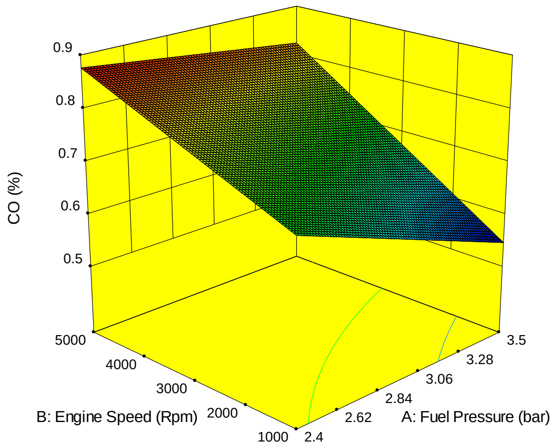
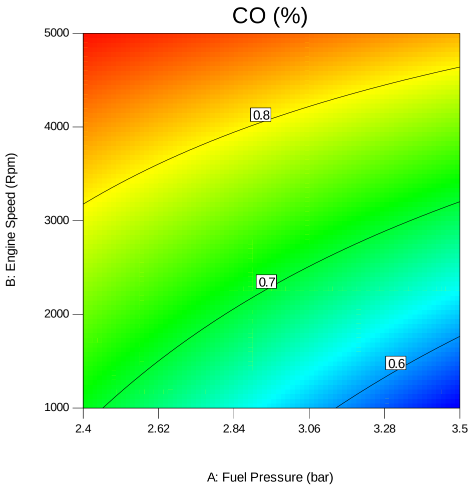


Figure 7: Interaction of fuel pressure and engine speed on CO emission

Contour plot (Figure 8) show that CO decreases when fuel pressure > 3 bar and engine speed is lower. In Table 7, assuming Fuel pressure (A), engine speed (B), ANOVA (Analysis of variance) shows that the interaction (AB) are significant at the 1% level, And also; by the appearance of the $R^2 = 0.98$, we can be sure that the model is reliable.



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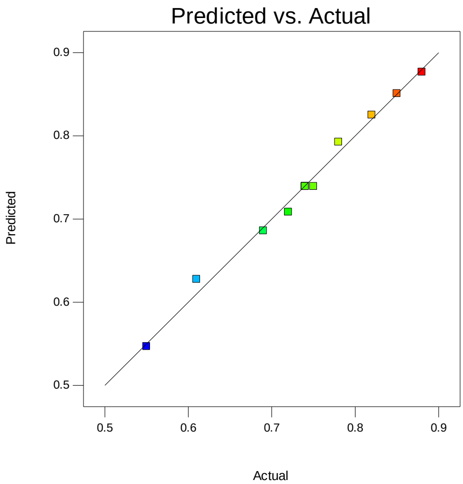


B

Figure 8: Contour plot (a) Comparison of actual results with the predicted results of CO emission (b)

Table 7: Analysis of variance of CO emission

Source	Sum of Squares	df	Mean Square	F. Value	p-value Prob > F
Model	0.095	3	0.032	363.18	< 0.0001

A-Fuel Pressure	0.017	1	0.017	195.92	< 0.0001
B-Engine Speed	0.075	1	0.075	858.89	< 0.0001
AB	3.025E-003	1	3.025E-003	34.73	0.0002
Residual	7.840E-004	9	8.711E-005		
Lack of Fit	7.040E-004	5	1.408E-004	7.04	0.0410
Pure Error	8.000E-005	4	2.000E-005		
Cor Total	0.096	12			

CO_2 emission

Figure 9 indicates that higher fuel pressure increases CO_2 (due to improved combustion) and higher engine speed reduced CO_2 (due to shorter combustion time) [31].

According to Figure 9 and the results of analysis of variance in Table 8, it can be seen that the two variables of fuel pressure and engine speed have a significant effect on CO2 gas at the level of 1%. The regression equation between independent variables and dependent variables is shown in Equation 7, which can also predict and detect different values of variables. In this equation, A is the amount of fuel injection pressure (bar) and B is engine speed (Rpm).

$$CO_2 = 14.38 + 0.43\,A - 0.45\,B + 0.1\,AB - 0.19\,A^2 - 0.14\,B^2 \quad (7)$$

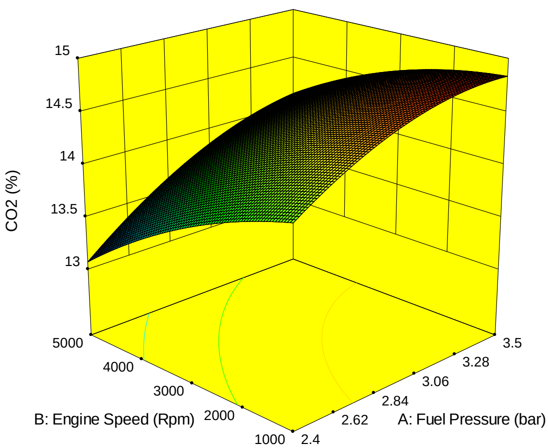
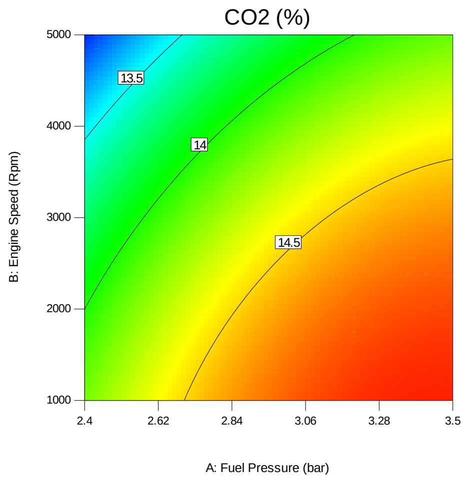


Figure 9: Interaction of fuel pressure and engine speed on CO_2 emission

The contour diagram indicates that with increasing fuel injection pressure and decreasing engine speed, CO_2 emission increases and improves the quality of combustion.

For model validation, ANOVA (Table 8) and Figure 10 indicates that fuel pressure (A) and engine speed (B) are statistically significant at the 1% level. Additionally, R^2 = 0.97 demonstrates strong agreement between the model's predicted data and the experimental data.



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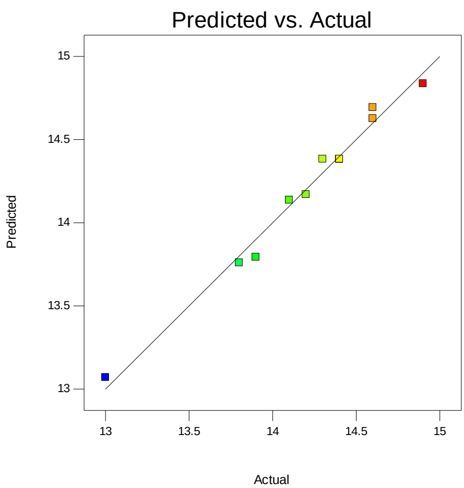


B

Figure 10: Contour plot (a) Comparison of actual results with the predicted results of CO_2 emission (b)

Table 8: Analysis of variance of CO2 emission

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	2.63	5	0.53	88.36	< 0.0001
A-Fuel Pressure	1.13	1	1.13	189.54	< 0.0001
B-Engine Speed	1.22	1	1.22	204.40	< 0.0001
AB	0.040	1	0.040	6.73	0.0357
A2	0.099	1	0.099	16.71	0.0046
B2	0.054	1	0.054	9.06	0.0197
Residual	0.042	77	5.944E-003		
Lack of Fit	0.034	3	0.011	5.60	0.0647
Pure Error	8.000E-003	44	2.000E-003		
Cor Total	2.67	12			

HC emission

Figure 11 illustrates the impact of fuel injection pressure and engine speed on unburned hydrocarbon (HC) emissions. An increase in both fuel pressure and engine speed leads to a reduction in HC emissions [32]. This trend is attributed to improved combustion efficiency under higher pressure and speed conditions.

Figure 11 and the results of analysis of variance in Table 9 show that the two variables of fuel pressure and engine speed have a significant effect on HC emission at the level of 1%. The regression equation between independent variables and dependent variables is shown in Equation 8, which can also predict and detect different values of variables [33].

$$HC = 117.45 - 9.5\,A - 52.83\,B - 0.75\,AB - 0.57\,A^2 + 35.43\,B^2 \qquad (8)$$

where:

A = Fuel injection pressure (bar),

B = Engine speed (rpm).

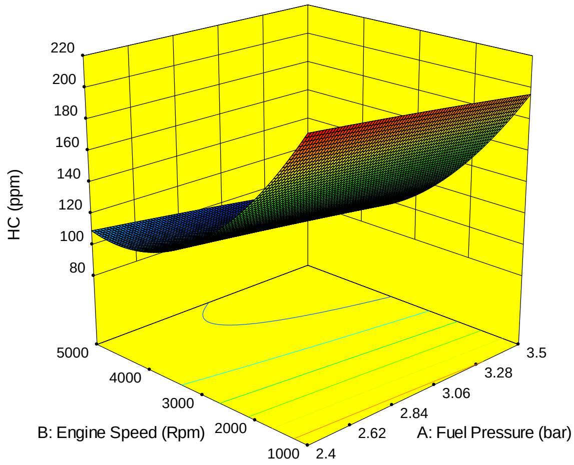
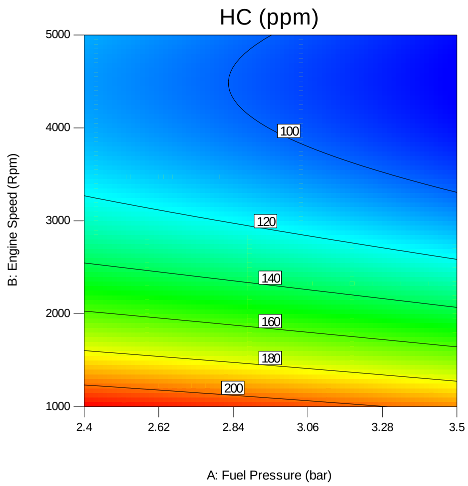
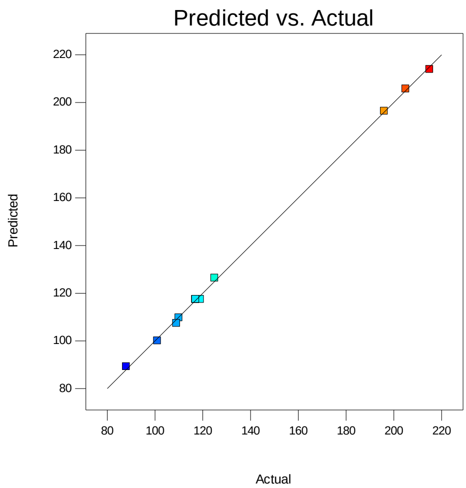


Figure 11: Interaction of fuel pressure and engine speed on HC emission

The contour plot (Figure 12) reveals that HC emissions decrease with higher fuel pressure and lower engine speeds.An analysis of variance (ANOVA) for this pollutant (Table 9) indicates a statistically significant relationship at the 1% level between fuel pressure (A), engine speed (B), and the quadratic term of engine speed (B^2). However, the interaction term (AB) and the quadratic term of fuel pressure (A^2) do not show a significant relationship. Additionally, R^2 = 0.99 indicates that 99% of the variability in HC emissions is explained by the predictors. This high prediction accuracy further confirms the model's validity.



A



B

Figure 12: Contour plot (a) Comparison of actual results with the predicted results of HC emission (b)

Table 9: Analysis of variance of HC emission

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	21299.11	5	4259.82	2460.74	< 0.0001
A- Fuel Pressure	541.50	1	541.50	312.80	< 0.0001
B-Engine Speed	16748.17	1	16748.17	9674.78	< 0.0001
AB	2.25	1	2.25	1.30	0.2918
A2	0.89	1	0.89	0.52	0.4956
B2	3467.18	1	3467.18	2002.86	< 0.0001
Residual	12.12	7	1.73		
Lack of Fit	8.92		2.97	3.72	0.1186
Pure Error	3.20	4	0.80		
Cor Total	21311.23	12			

Conclusion

This study investigated the effects of fuel injection pressure and engine speed on combustion parameters (λ, ignition advance) and exhaust emissions (CO, CO_2, HC) in a gasoline engine using Response Surface Methodology (RSM). Key findings include:

1- Stoichiometric Ratio (λ):

- Increased fuel pressure reduces λ (richer mixture), while higher engine speed increases λ (leaner mixture).
- Range: λ varied from 1.015 (3.5 bar, 1,000 rpm) to 1.044 (2.4 bar, 5,000 rpm).

2- Ignition Advance:

- Higher fuel pressure delays ignition, whereas higher engine speed advances it.
- Range: Ignition advance ranged from 7° (3.5 bar, 1,000 rpm) to 37° (2.4 bar, 5,000 rpm).

3- CO Emissions:

- Increased fuel pressure reduces CO, while higher engine speed raises it due to leaner combustion.

- Range: CO levels spanned 0.54% (3.5 bar, 1,000 rpm) to 0.88% (2.4 bar, 5,000 rpm).

4- CO_2 Emissions:

- Higher fuel pressure increases CO_2 (improved combustion), while higher engine speed reduces it.
- Range: CO_2 levels ranged from 13.1% (2.4 bar, 5,000 rpm) to 14.8% (3.5 bar, 1,000 rpm).

5- HC Emissions:

- Increased fuel pressure and engine speed lower HC emissions.
- Range: HC levels varied from 86 ppm (3.5 bar, 5,000 rpm) to 212 ppm (2.4 bar, 1,000 rpm).

6- Fuel System Implications:

- Declining fuel pressure (due to pump inefficiency, clogged filters, or injector issues) degrades combustion quality, increasing λ, ignition advance, and emissions (CO, HC).
- Optimal pressure: Maintaining fuel pressure ≥3.5 bar with regular system maintenance minimizes emissions.

7- Environmental Impact:

- Proper fuel system design and pressure control can significantly reduce urban air pollution from gasoline engines.

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