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Research Article

Effect of Gasoline-AVGAS Blends on Exhaust Emission of Gasoline Engine Using Taguchi Approach

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Abstract

In this study, aviation gasoline AVGAS and gasoline were mixed in certain proportions and TSI was applied in a gasoline engine. Emission results were observed by increasing the octane rating of fuel blends with Avgas. Experimental studies were carried out using the taguchi method. The accuracy of the observed emission values is supported by ANOVA analysis and contour graphs and compared with gasoline reference fuel.

Keywords: Avgas, Gasoline, TSI, Engine Emissions

Taguchi Yaklaşımı Kullanılarak Benzin-AVGAS Karışımlarının Benzinli Motorun Egzoz Emisyonlarına Etkisi

Özet

Bu çalışmada, havacılık benzini AVGAS ve benzin belirli oranlarda karıştırılarak TSI benzinli motorda kullanılmıştır. Avgas ile yakıt karışımlarının oktan derecesi artırılarak emisyon sonuçları gözlemlenmiştir. Deneysel çalışmalar taguchi yöntemi kullanılarak yapılmıştır. Gözlemlenen emisyon değerlerinin doğruluğu ANOVA analizi ve kontur grafikleri ile desteklenmiş ve benzin referans yakıtı ile karşılaştırılmıştır.

Anahtar Kelimeler: Avgas, Benzin, TSI, Motor Emisyonu

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1. Introduction

Avgas is a high octane fuel that is obtained by formulating gasoline and called aviation gasoline. The reason for the high octane is the lead tetra ethly (TEL) it contains. Due to the high octane level, the air-fuel mixture can be compressed at a higher rate without ignition [1].

The ratio of less and highly volatile components in Avgas is less than the gasoline used in automobiles. Contains a certain percentage of lead tetra-ethly to reduce the burning rate of gasoline [2]. Physical and chemical properties of Avgas fuel are given in Table 1.

Avgas contains Tetra Ethly Lead (TEL), which is an additive banned in automotive precursors in the European Union for environmental reasons [4, 5]. TEL is an additive added to aviation fuels to help prevent knock [6, 5]. Considering the benefits of TEL, as it is known from the problems in automotive fuels, lead compounds of TEL form a protective layer in the valve seat and prevent the abrasion of soft valve seats. Without a TEL, small areas of the soft metal valve seat are fused to the valve and the valve is pulled from the seat surface. Once attached to the valve, they form an abrasive surface that further damages the valve seat. This combination of action is known as valve seat collapse (VSR) as the valve seat wears and enters the cylinder head. The solutions for this are either using VSR additives or using hardened valve seats resistant to this action [1].

Another problem with unleaded fuels is the octane rating. Octane rating is a measure of how resistant a fuel is to knock; the higher the octane ratio, the more the fuel-air mixture can be compressed without ignition.

The advantage of higher octane fuels is that a higher compression ratio or overfill rate can be used, resulting in a higher engine cycle efficiency.

TSI, which consists of the initials of Turbo Spercharger Injection, is defined as a turbocharged and direct injection engine. Generally used in small volume engines such as 1.2 lt [7].

As a result of researches in the literature, it has been determined that alternative mixtures with different fuel types are mostly made on diesel engines and gasoline engines with older technologies. The most important factor that makes this study important is the increase in the importance of gasoline engines and alternative fuels as a result of the prohibition of its use in passenger cars in many European countries, even in the Middle East countries, as a result of the harmful emissions caused by diesel fuel. Today, it is a work to be done on TSI engines, which is one of the most modern, efficient technologies in gasoline engines, where the power obtained from unit volume is very high and therefore has low fuel consumption.

The aim of this study is to investigate the emission values of Avgas, which is a highly compressible fuel, by using TSI in an engine.

2. Material and Method

Experiments in this study were carried out in Selcuk University Technology Faculty Mechanical Engineering Engine Test and Fuel Laboratory. The experimental setup consists of a four-stroke four-cylinder Volkswagen TSI brand gasoline engine, a hydraulic dynamometer to load the engine and an emission measuring device to measure the exhaust gas emissions. The schematic view of the experimental setup is shown in Figure 1.

Table 1. Physical and chemical properties of AVGAS [3]

Property	Maximum	Minimum
Knock Degree, Lean Mixture (Engine Method), Octane Number		99.5
Knock Degree, Rich Mix (Supercharging Method), Number of Performances		130
Freezing point °C	-58	
Distillation Endpoint °C	170	
Reid Vapor Pressure @38°C, kPa	49	38
Sulfur Content %m	0.05	
Tetraethyl Lead Content gPb/l		
Avgas 100	0.85	
Avgas 100LL	0.56	
Explosive Limits (% of volume in air)	7.6	1.5
Initial Boiling Point Range °C	170	24
Steam Pressure @37.8°C, psia(Reid VP)	7	5.5
Specific Gravity (Water = 1) @15.6 °C	0.74	0.68
Flash Point °C	< -37	
Autoignition Temperature °C	440	
Vapor Density (air = 1)	>1	
Evaporation Rate (nBuAc=1)	>1	
Percent Volatility	%100	
Color		
Avgas 100	Green	
Avgas 100LL	Blue	
Physical Form	Liquid	
Smell	Gasoline	

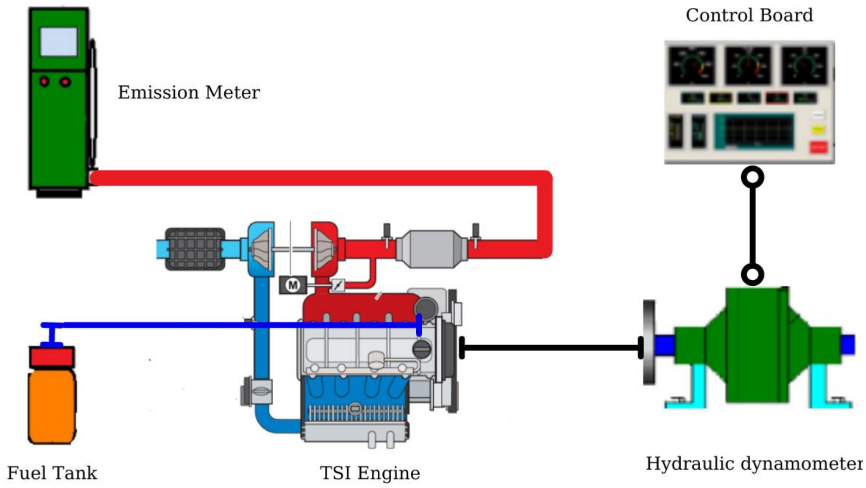


Figure 1. Schematic view of the experimental setup

The experimental setup consists of a four-stroke four-cylinder Volkswagen TSI brand gasoline engine, a hydraulic dynamometer to load the engine and an emission measuring device to measure the exhaust gas emissions. The schematic view of the experimental setup is shown in Figure 1. Experiments were carried out under full load conditions and full throttle opening. The engine was run with gasoline for a while before starting experiments for fuel mixtures. In each fuel test, the previous fuel was completely purged from the engine. Experiments were carried out on the same day to prevent data deviations due to the humidity and temperature difference in the atmosphere. In order to increase the reliability of the experimental results, the experiments were carried out in three replicates and the values were averaged.

2.1. Experiment Engine

The experiments were carried out on the TSI engine of the Volkswagen brand. Technical specifications of the test engine are given in Table 2 and the test engine is given in figure 2.

Figure 2.Experiment engine

2.2. Test Fuels

Three different volumetric fuels have been prepared for use in tests. Fuels are determined as A0 (Gasoline 100%, Avgas 0%), A5 (Gasoline 95%, Avgas 5%), A10 (Gasoline 90%, Avgas 10%) and A15 (Gasoline 85%, Avgas 15%) (Figure 3).

Table 2. Test engine technical specifications

Engine Code	CBZB
Structure	Production engine
Number of Cylinders	4
Valves Per Cylinder	2
Volume	1197 cm^3
Cylinder Diameter	71 mm
Stroke	75.6 mm
Compression Ratio	10:1
Maximum Power Output	500 rpm rotation 77 kW
Maximum Torque	1500-3500 rpm in the range of 175 Nm
Control unit	Continental Simos 10.1
Fuel	95 octane super unleaded
Exhaust Finishing	Three-way catalytic converter, linear lambda probe before catalytic converter, sudden movement lambda probe after catalytic converter
Emission Standard	EU5

Figure 3.Test fuels

2.3. Hydraulic Dynamometer

Connected to the engine, the engine was loaded at desired revolutions. Technical features of hydraulic dynamometer are given in Table 3.

2.4. Emission Meter

Emissions resulting from combustion are important operating parameters for the engine. Bosch BEA 350 model emission measuring device was used in the experiments to measure these parameters. Technical specifications are given in Table 4.

2.5. Experimental Design

2.5.1. Taguchi Method

Taguchi is an effective statistical method that searches for optimum working conditions with a small number of tests and reduces time and price through experiments [8]. Taguchi technique; It is a technique that increases quality, speeds up research and development activities and reduces costs [9].

It evaluates the experimental results obtained in Taguchi experimental design by converting them into signal to noise (S / N) ratios. While converting the test results into S / N ratio, according to the target, the Big Value is the Best, the Small Value is the Best, the Nominal Value is the Best. Whichever target is used, the resulting largest S / N ratio is the best result. [10, 11]. S/N rate of;

The biggest is the best; the desired value of the target value is the highest value. Equation 1 gives the formula for the greatest best S / N ratio [12, 13].

$$S/N = -10log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (1)$$

Table 3. Hydraulic dynamometer specifications

Brake Model	BT-190 FR
Maximum Braking Force	100 kW
Maximum Speed	6000 d/d
Maximum Moment (Torque)	750 Nm
Brake Water Working Pressure	0-2 kg/cm^2
Water Requirement for Maximum Power	2,3 m^3/h
Maximum Brake Water Outlet Temperature	80 °C
Torque Measurement	Elektronik Load-Cell
Rotation Direction	Right and Left

Table 4.Emissions meter specifications

Bosch BEA 350	**Measuring Range**	**Precision**
CO	0,000 – 10,00 (%)volumetric	% 0,001
CO_2	0,00 – 18,00 (%)volumetric	% 0,01
HC	0 – 9999 ppm volumetric	1 ppm
NO_X	0 – 5000 ppm volumetric	1 ppm
O_2	0,00 – 22,00 (%)volumetric	% 0,01
Lamda (λ)	0,500 – 9,999	0,001
Turbidity Degree	0 – 100 (%)	% 0,1

The smallest the best; the desired value of the target value is the smallest value. Equation 2 gives the formula for the smallest best S / N ratio [12, 13].

$$S/_N = -10log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (2)$$

The target value is the best; the target value has the desired value and the goal is to reach this value. Equation 3 is the best S / N ratio formula for the target value [12, 13].

$$S/_N = 10log\left[\frac{y^2}{s^2}\right] \quad (3)$$

In the designed experiment, different levels were selected for two factors and L9 (3 ^ 2) experiment design matrix was used. Selected factors and levels are given in table 5 and L9 (3 ^ 2) experiment design matrix is given in table 6.

Table 5.Taguchi method factors and levels

Factors	Level 1	Level 2	Level 3
A-Engine Speed (Rpm)	1500	2500	3500
B-Avgas (%wt)	5	10	15

Table 6. L9 (3 ^ 2) experiment matrix

Run	*Engine Speed (Rpm)-A*	*Avgas (%wt)-B*
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

3. Results and Discussion

3.1. Experiment Results

Tests were carried out according to the experimental order in the L9 orthogonal array designed with Taguchi method. Test results are shown in table 7.

Considering the experimental results, the taguchi method was applied. Model reliability of each answer according to Taguchi method is shown in Table 8.

As seen in the table, the taguchi method provides a model reliability of over 98% for all answers. This shows that the experiments and the values to be predicted are reliable.

3.2. ANOVA Analysis

ANOVA analysis is performed to see how factors affect output parameters. Based on the P value generated from this analysis, it can be concluded which control factor affects the output parameter most. Output parameters strongly depend on the control factors with the lowest P value [14]. Anova analysis results of emission parameters are given in Table 10. The ANOVA table divides the variability in responses into separate parts for each of the factors. It then tests the statistical significance of each factor by comparing the mean square with the experimental error estimate. If the p value of a factor is less than 0.05, it is an indicator that it has more effect and importance in the model created [15].

In this case, the engine speed is important in predicting the answers with a confidence degree of 99%. The Avgas factor is important with a 99% confidence level in predicting HC and NO_x emission responses, and a 95% confidence level in predicting CO, CO_2 and O_2 responses.

Table 7.Test results

No.	A Engine Speed	B-Avgas	CO	CO_2	HC	O_2	NO
1	1500	5	0,978	8,03	76	11,26	894
2	1500	10	0,897	7,35	69	12,51	815
3	1500	15	0,786	6,4	64	13,11	758
4	2500	5	1,067	10,12	64	4,62	2545
5	2500	10	1,018	9,67	58	5,32	2413
6	2500	15	0,934	8,76	55	5,92	2214
7	3500	5	0,376	12,95	51	1,02	2998
8	3500	10	0,331	12,58	48	1,17	2776
9	3500	15	0,305	12,08	44	1,21	2581

Table 9.Model reliability of the responses

Response	R^2 (%)	Adj. R^2 (%)
CO	99,86	99,72
CO_2	98,71	97,42
HC	99,76	99,52
O_2	99,97	99,93
NO	99,98	99,97

3.3. Determination of Optimum Factor Levels

Figure 4 shows the effects of changes in factors affecting responses using the Taguchi method. The largest S / N ratio provides the best levels for parameters.

When Figure 4-a and Figure 4-c are examined, optimum factor levels for CO emission and HC emission were determined as 3500 rpm and 15% Avgas. The optimum factor combination for these answers is 'A3-B3'.

When Figure 4-b and Figure 4-e are examined, optimum factor levels for CO_2 emission and NO_x emission were determined as 1500 rpm and 15% Avgas. The optimum factor combination for these answers is 'A1-B3'.

When Figure 4-d is examined, optimum factor levels for O_2 emission were determined as 3500 rpm and 5% Avgas, and the optimum factor combination was determined as 'A3-B1'.

3.4. Normal Probability Plots

In Figure 5, normal-probability graphs are shown according to the S / N ratios of the answers. Normal probability plot is a graphical technique for evaluating whether a data set is approximately normally distributed [16].

When Figure 5 is examined, we can see that the data set for all answers is reliable. Since the data falls in a straight line, we can assume that we have a normal distribution.

3.5. Contour Plots

Contour plot is a graphic technique to represent a 3-dimensional surface by drawing fixed z slices called contours in a 2-dimensional format. After positioning the two factors in the x and y coordinates, the values given by the response factor in the z coordinate are shown in color in these graphs.

In Figure 6, contour graphs are given according to the engine speed and Avgas ratio of each response. In the graphs min. values (open fields) are requested.

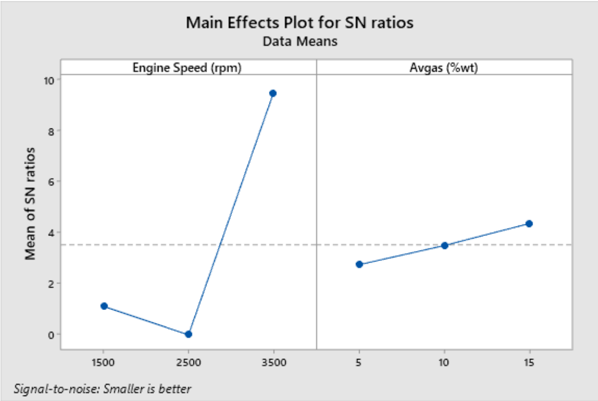
If emission parameters are examined; The CO emission contour graph is given in figure 6-a. The emission value is at its highest within the limits of approximately 1600 rpm and 2700 rpm and did not change much with the engine speed. However, as the Avgas ratio is increased, decreases in emission are observed. While the emission value gradually increases with engine speed until it reaches approximately 1600 rpm, it decreases after approximately 2700 rpm. Increasing the Avgas ratio has shown a continuous decrease in CO emissions.

CO_2 emission contour graph is given in Figure 6-b. Although it increases with the engine speed, the contour lines slope upwards and the emission value decreases as the Avgas ratio increases. The lowest CO_2 emission values were found to be between 12.5% and 15% Avgas. The contour graph of HC emission is given in Figure 6-c. In HC emission, there is a situation similar to the CO_2 emission for the Avgas ratio. However, with the engine speed, HC emission decreased, not increased.

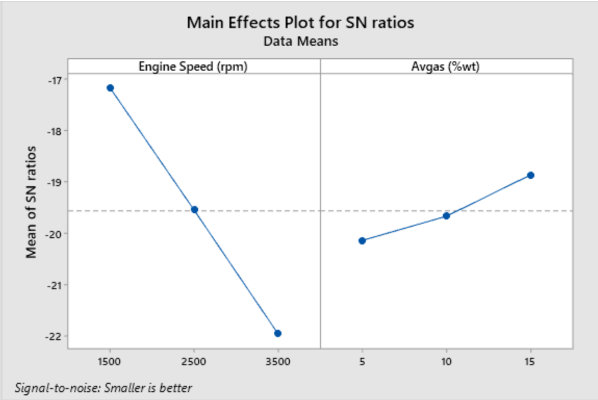
The O_2 emission contour graph is given in Figure 6-d. A decrease in O_2 emission values was observed with the engine speed. However, increasing the Avgas ratio increases the O_2 emission values. NO_x emission contour graph is given in Figure 6-e. There has been a decrease in NO_x emission values by increasing the Avgas ratio. It increases with engine speed. However, despite the increase in engine speed after about 2700 rpm, the Avgas ratio was effective in the decrease of emission values.

Table 9.Anova analysis results of emission parameters

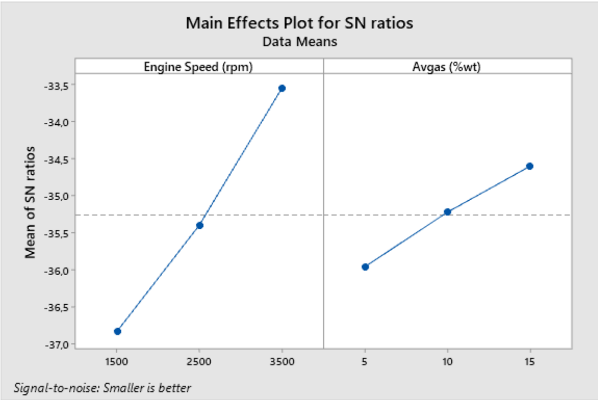
	Factors	DF	Seq SS	Adj SS	Adj MS	F	P
CO	Engine Speed (rpm)	2	162,221	162,221	81,1105	1404,56	0,000
	Avgas (%wt)	2	3,963	3,963	1,9816	34,31	0,003
	Residual Error	4	0,231	0,231	0,0577		
	Total	8	166,415				
CO_2	Engine Speed (rpm)	2	34,2573	34,2573	17,1287	142,49	0,000
	Avgas (%wt)	2	2,4979	2,4979	1,2490	10,39	0,026
	Residual Error	4	0,4808	0,4808	0,1202		
	Total	8	37,2361				
HC	Engine Speed (rpm)	2	16,3263	16,3263	8,16314	705,59	0,000
	Avgas (%wt)	2	2,7967	2,7967	1,39835	120,87	0,000
	Residual Error	4	0,0463	0,0463	0,01157		
	Total	8	19,1693				
O_2	Engine Speed (rpm)	2	661,483	661,483	330,741	5858,53	0,000
	Avgas (%wt)	2	4,259	4,259	2,130	37,72	0,003
	Residual Error	4	0,226	0,226	0,056		
	Total	8	665,968				
NO_x	Engine Speed (rpm)	2	200,122	200,122	100,061	12885,02	0,000
	Avgas (%wt)	2	2,593	2,593	1,297	166,98	0,000
	Residual Error	4	0,031	0,031	0,008		
	Total	8	202,747				



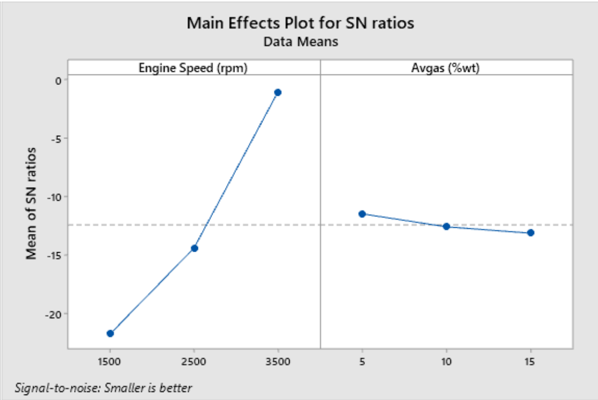
a. CO



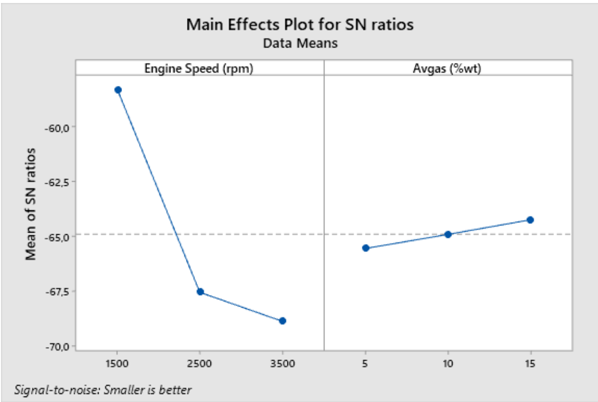
b. CO_2



c. HC

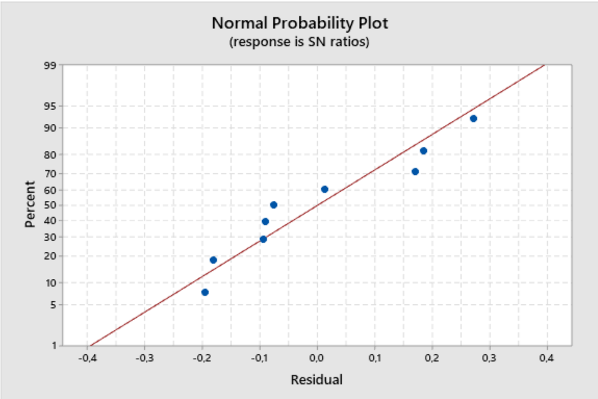


d. O_2

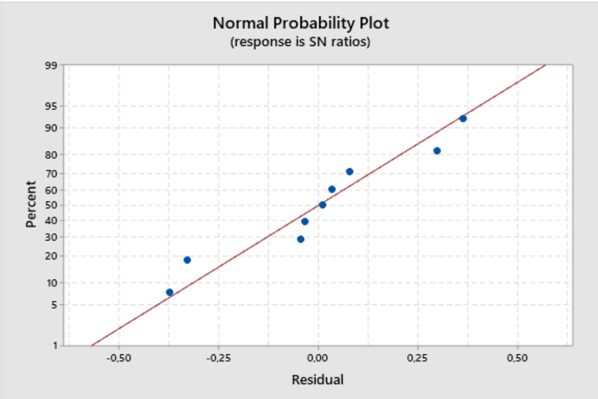


e. NO_x

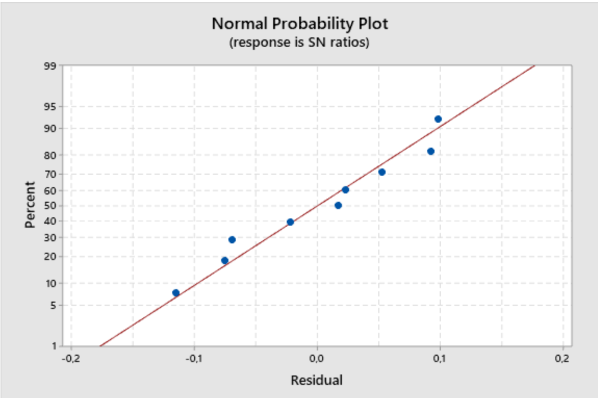
Figure 4. Main effect graphs according to S / N ratios



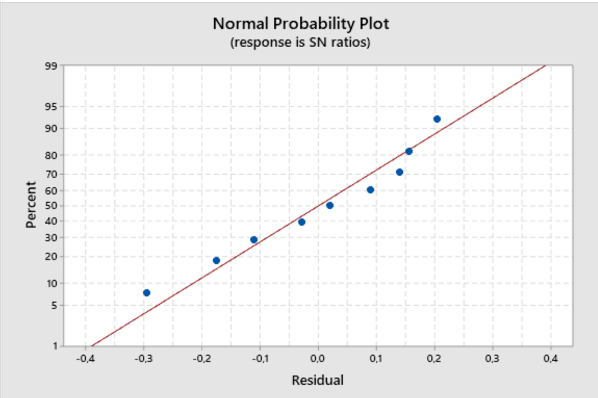
a. CO



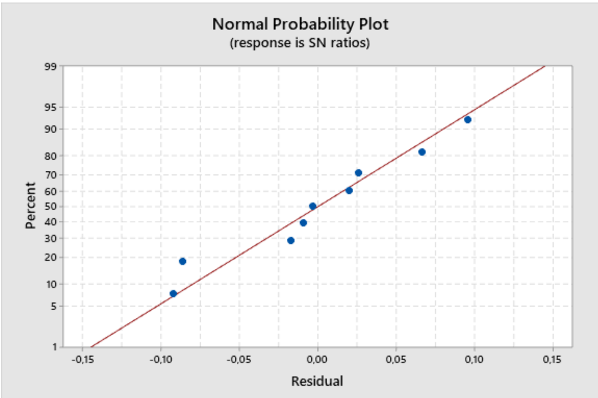
b. CO_2



c. HC

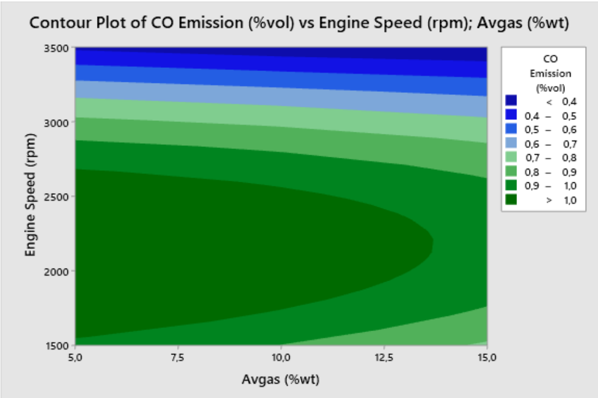


d. O_2

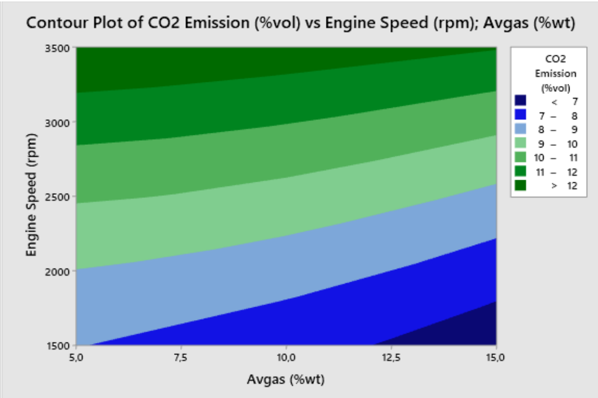


e. NO_x

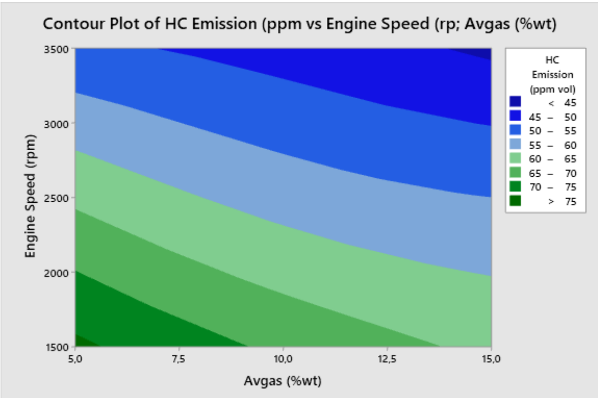
Figure 5. Normal-Probability graphs



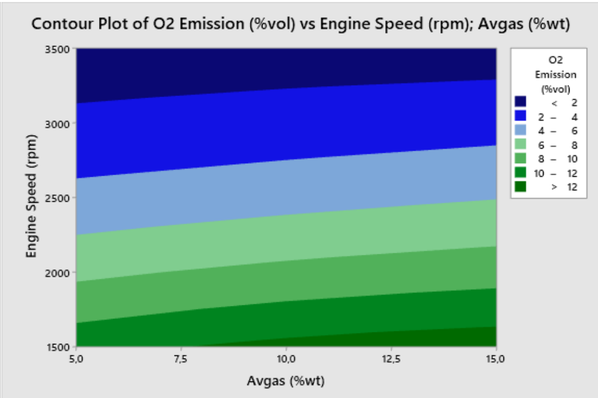
a. CO



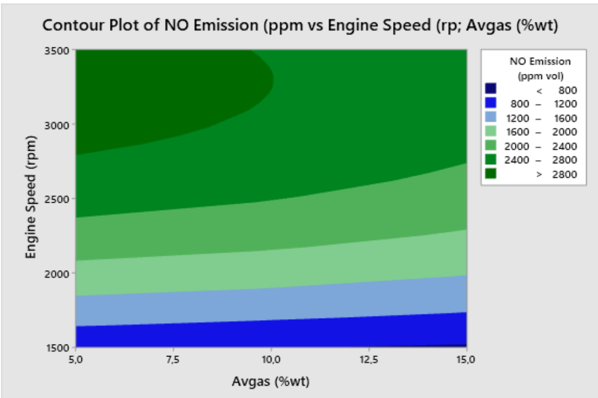
b. CO_2



c. HC



d. O_2



e. NO_x

Figure 6.Contour plots

3.6. Comparison with Gasoline Reference Fuel

Test results of Avgas blended fuels are compared with the results of the gasoline reference fuel in the graphs below.

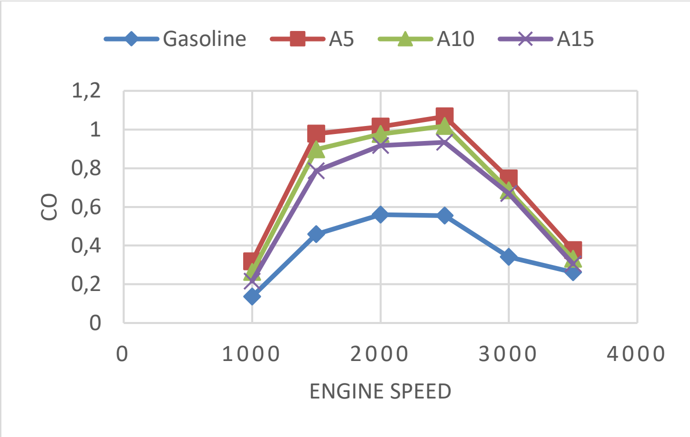


Figure 7. Graph of CO emission test responses

Depending on engine speed ranges; CO emission changes due to gasoline, A5, A10 and A15 fuels are shown in figure 7. The lowest CO emissions were measured as 0.136% at 1000 rpm in gasoline, 0.216% at 1000 rpm in A15 fuel mixture, 0.263% at 1000 rpm in A10 fuel mixture and 0.263% at 1000 rpm in A5 fuel mixture. . The use of Avgas has increased the CO emission values compared to gasoline. However, increasing the amount of Avgas after 10% avgas mixture showed a decrease in CO emission.

CO emission value arises when there is insufficient oxygen or in the absence of complete combustion. However, regional oxygen deficiency may also occur due to the inhomogeneity of fuel mixtures. CO emission is an important parameter as it is an important function of the excess air coefficient and indicates the power that cannot be used in the engine among the combustion products [17].

CO emission values increase due to insufficient amount of air intake at low revs of the engine when the turbocharger is not active. With the activation of the turbocharger after 2500 revs, better combustion occurred in all fuel mixtures and CO emission values decreased.

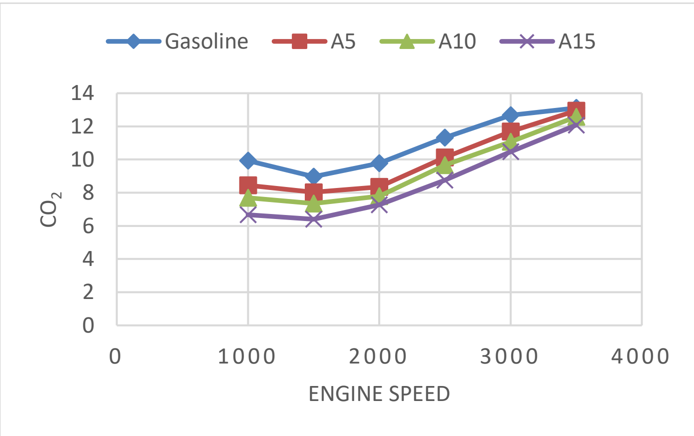


Figure 8.Graph of CO_2 emission test responses

Depending on engine speed ranges; CO_2 emission changes due to gasoline, A5, A10 and A15 fuels are shown in figure 8. The lowest CO_2 emission values were measured as 6.4% in A15 fuel mixture, 7.35% in A10 fuel mixture, 8.03% in A5 fuel mixture and 8.97% in gasoline at 1500 rpm. CO_2 emission increases with the engine speed after 1500 rpm. However, the use of Avgas has reduced CO_2 emissions.

Combustion worsens as the load increases at low revs and CO_2 emissions decrease. With the increase of engine speed, the turbocharger is activated and more oxygen is taken inside. Therefore, burning is getting better. As a result, CO_2 emissions are increasing. In the rich fuel mixture, the C atom increases and the fuel cannot find oxygen. Therefore, CO_2 emission is decreasing. It can be said that Avgas reduces CO_2 emission due to the resistance of TEL, which is an additive, against combustion.

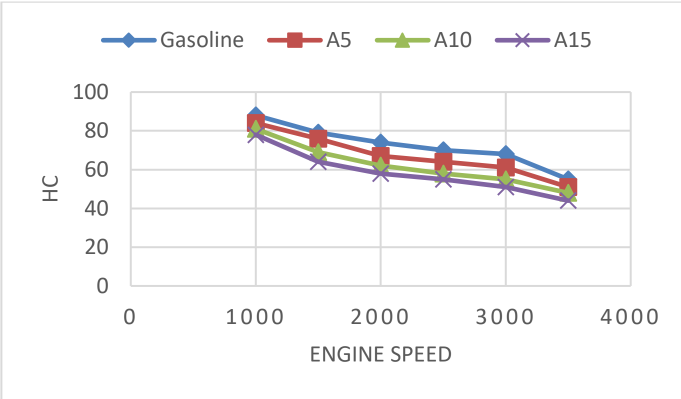


Figure 9. Graph of HC emission test responses

Depending on engine speed ranges; HC emission changes due to gasoline, A5, A10 and A15 fuels are shown in figure 9. The lowest HC emission values were measured at 3500 rpm, 44 ppm in A15 fuel mixture, 48 ppm in A10 fuel mixture, 51 ppm in A5 fuel mixture and 55 ppm in gasoline. HC emission decreases with engine speed. The use of Avgas has also reduced HC emissions.

HC emission consists of unburned fuel particles discharged from the exhaust. The formation of HC emission occurs because the fuel cannot find enough oxygen and time for combustion and cannot reach the ignition temperature [18]. With the increase of engine speed, a better homogeneous mixture occurs in the cylinder. As a result, HC emissions tend to decrease. In addition, as the temperature inside the cylinder increased with the use of Avgas, HC emissions decreased.

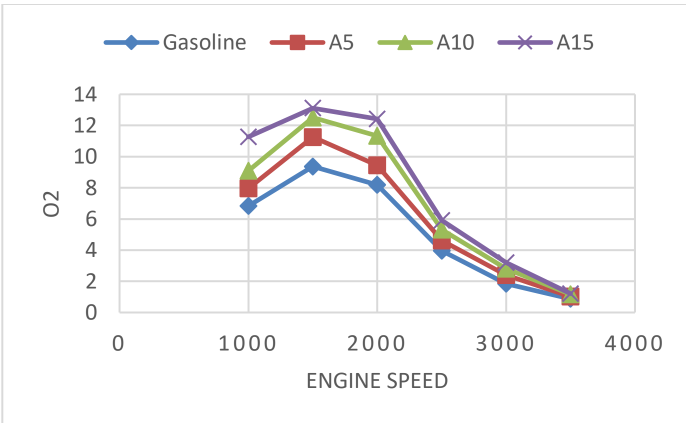


Figure 10. Graph of O_2 emission test responses

Depending on engine speed ranges; O_2 emission changes due to gasoline, A5, A10 and A15 fuels are shown in figure 10. The lowest O_2 emissions were measured as 0.87% in gasoline, 1.02% in A5 fuel, 1.17% in A10 fuel and 1.21% in A15 fuel at 3500 rpm, respectively. It was seen that the highest O_2 emission occurred at 1500 rpm. After this cycle, O_2 emission tended to decrease. The use of Avgas has increased O_2 emissions.

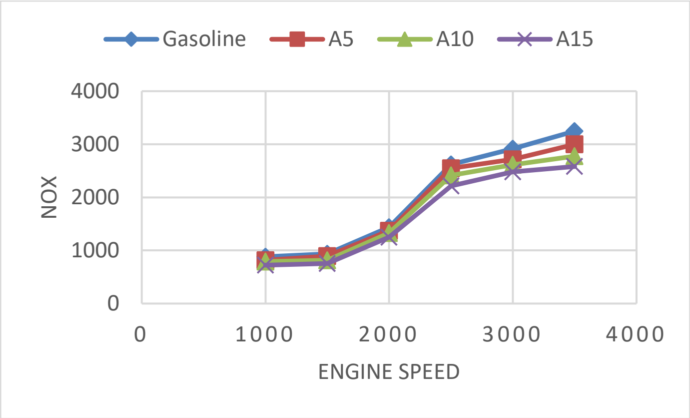


Figure 11. Graph of NO_X emission test responses

Depending on engine speed ranges; NO_x emission changes due to gasoline, A5, A10 and A15 fuels are shown in figure 11. The lowest NO_x emission values were measured at 1000 rpm, respectively 723 ppm in A15 fuel, 791 ppm in A10 fuel, 816 ppm in A5 fuel and 882 ppm in gasoline. An increase in NO_x emission values was observed with the engine cycle. However, the use of Avgas has reduced the NO_x emission values in each cycle.

With the increase in load, the average gas temperature in the cylinder increases, which increases NO_x emission [19]. At the high temperatures reached as a result of combustion, nitrogen reacts with oxygen and NO_x is formed [20]. However, it can be said that NO_x emissions are reduced with the resistance to combustion and direct injection technology in fuel mixtures containing Avgas. When compared with the O_2 emission values in the separate figure 16, it is seen that it makes a complete mirroring and these two graphs confirm each other.

4. Result

CO_2, HC and NOx emissions decreased as the Avgas ratio was increased in fuel mixes. There was no difference in CO emission at low and high speeds, but an increase was observed in middle cycles. Although there is an increase in O_2 emission compared to gasoline, the difference between values has decreased as the engine speed increases. In experiments supported by the Taguchi method, it has been observed that the use of Avgas in gasoline generally reduces emission parameters. It is thought that Avgas fuel will increase engine performance values due to its high octane rating. For this reason, it is recommended for further studies.

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