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Ecological effects of changes in Air-Fuel Ratio of a gasoline engine on exhaust harmful gases emissions

Hristo Kanevski[1,*], Slavi Lyubomirov[1], Stanislav Asenov[1], Anatoliy Parushev[1], Slaveya Petrova[2]

[1]Faculty of Physics and Technologies, University of Plovdiv "Paisii Hilendarski", 24 Tsar Asen Str., Plovdiv, 4000, BULGARIA
[2]Faculty of Biology, University of Plovdiv "Paisii Hilendarski", 24 Tsar Asen Str., Plovdiv, 4000, BULGARIA
*Corresponding author: kanevski@uni-plovdiv.bg

Abstract. The present study examines the effect of the air-fuel mixture ratio on harmful emissions from a gasoline engine, analyzed from an ecological perspective. The experiments were carried out with a BMW 318 gasoline engine equipped with a MegaSquirt 3 electronic control unit and TunerStudio MS software, as well as a Kane AUTOplus gas analyzer. The concentrations of three gaseous pollutants - carbon monoxide (CO), carbon dioxide (CO_2) and unburned hydrocarbons (HC), were measured at different engine speeds and different air-fuel ratios. The obtained data were used to compile regression equations that describe the relationship between the air-fuel mixture ratio and the harmful emissions levels. The results show significant changes in gaseous pollutants' emissions depending on engine settings, which highlights the importance of optimizing these parameters to reduce both the environmental pollution and greenhouse gases levels into the atmosphere.

Key words: air pollution, traffic emissions, greenhouse gases, CO, CO_2, hydrocarbons.

Introduction

There are two types of vehicles' emissions that significantly degrade the environment, air quality and human health, namely greenhouse gases and air pollutants. The main greenhouse gas produced by motor vehicles is carbon dioxide (CO_2), while the second group includes carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), etc. Road transport was found to be responsible for about a 1/4 of the EU's total CO_2 emissions in 2019 (European Parliament, 2019). As the EU aims to achieve a 90% reduction in greenhouse gas emissions from transport by 2050 (COM, 2019), its efforts are mainly dedicated to reduce CO_2 emissions from motor vehicles (European Parliament, 2018).

The study of the influence of the air-fuel ratio on harmful emissions from gasoline engines is of key importance for improving the environmental performance of modern vehicles. In recent years, several studies have been devoted to the optimization of the air-fuel ratio (AFR) to reduce the emissions of pollutants such as carbon monoxide (CO) and hydrocarbons (HC) (Pikūnas et al., 2003; Schifter et al., 2013). The main parameter that affects the combustion process in gasoline engines is the stoichiometric air-fuel ratio, which for gasoline is about 14.7:1 (Seifert, 1979). However, under real-world conditions, engines often operate at different air-fuel ratios that vary depending on the engine operating mode and the fuel used (Turner et al., 2011). For example, when using ethanol-gasoline blends, the AFR changes, which affects the combustion characteristics and consequently the emissions (Liu et al., 2012; Iodice et al., 2016).

In the present study, we aimed to: i) measure CO_2, CO and HC exhaust emissions at different air-fuel mixture ratios in a gasoline engine equipped with a Mega Squirt 3 electronic control unit and a Kane AUTOplus gas analyzer; ii) process the data obtained using regression and correlation analyses to evaluate the relationships between air-fuel ratio and pollutants' emissions. This research will contribute to a better understanding of the environmental aspects of gasoline engine operation and the possibilities for optimizing their efficiency and environmental friendliness.

Materials and Methods

The research was conducted with a BMW 318 gasoline engine equipped with a MegaSquirt 3 electronic control unit and TunerStudio MS software. The engine is connected to a Kane AUTOplus gas analyzer that measures carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbons (HC) emissions.

Description of the experimental setup

1. Internal combustion engine:

Model: Gasoline engine from BMW 318

Technical characteristics: Four-cylinder, 1.8 liter, in-line internal combustion engine

2. Management system:

Model: Open hardware MegaSquirt 3 electronic engine control unit

Features: Allows precise adjustment of air-fuel ratio and other parameters.

3. Gas analyzer

Model: Kane AUTOplus

Functions: Measures CO, HC and CO_2 concentrations in exhaust gases.

Measuring range: CO (0-10%), HC (0-20000 ppm), (0-5000 ppm), CO_2 (0-20%).

4. Software: TunerStudio MS for setting and monitoring engine parameters (Fig. 1)

Features of TunerStudio MS: Intuitive user interface that allows quick and efficient tuning of engine parameters. Provides real-time data monitoring including engine RPM, coolant temperature, manifold pressure and other important parameters.

Ignition Tuning and Fuel Maps: Tools to create and edit ignition and fuel maps that allow optimization of engine performance under various conditions.

Measurement procedures

1. Design of the experimental setup:

The engine is mounted on a laboratory bench, allowing monitoring of its main parameters and work processes. The MegaSquirt 3 electronic control unit is configured to control the ignition and other engine parameters, using the Tuner Studio MS software product for configuration.

2. Procedure for changing the AFR:

Determining the air-fuel ratio range according to the manufacturer's specifications. The ratio of air to fuel mixture is changed in a range from 10:1 to 20:1.

3. Emission measurement:

Measurements are carried out at various engine speeds: 800, 1000, 1200, 1400, 1600, 1800, and 2000 rpm. For each combination of air-fuel ratio and rpm, the Kane AUTOplus gas analyzer records CO, CO_2 and HC concentrations. Measurements were repeated three times for each combination to ensure accuracy and repeatability of results.

Control and calibration

The Kane AUTOplus gas analyzer was calibrated before each series of measurements to ensure the accuracy of the measurements. The Mega-Squirt 3 system was checked and adjusted for each new combination of parameters to ensure the stability of the experimental conditions.

Precision and limitation of the study

The precision of the measurements was guaranteed by multiple repetitions and arithmetic mean of the obtained values. Limitations of the study include the influence of external factors such as ambient temperature and fuel quality, which may affect the results. This methodology provides a clear framework for conducting experiments and provides reliable and valid data for analyzing the influence of ignition angle on harmful emissions from a gasoline engine.

4. Data Analysis:

The raw data were analyzed using statistical methods to determine the correlation between the AFR and the harmful emissions' levels using MS Excel. Linear regression equations and coefficients have been used to analyze the relationships between the AFR and emissions at different engine speeds ($p<0.05$).

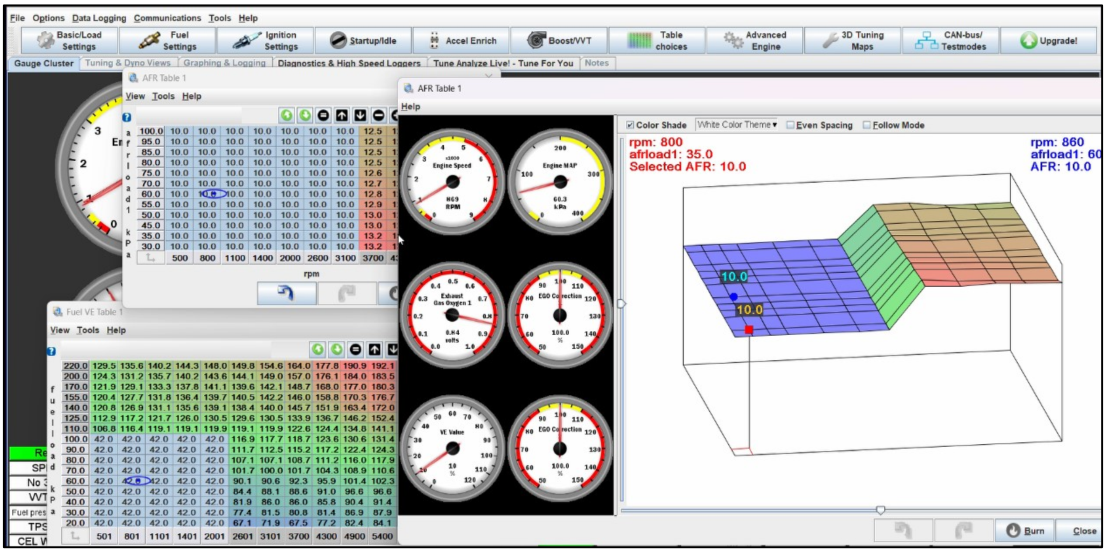

Fig. 1. Tuner Studio MS

Fig. 2. Experimental stand for carrying out the research.

Results

Experimental studies were conducted to measure the harmful emissions of carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbons (HC), released during the operation of a gasoline engine with internal combustion, operating at different air-fuel mixture ratios (from 10:1 to 20:1) and at different engine speeds (from 800 to 2000 rpm).

The results obtained on the change of CO_2 depending on the ratio of air-fuel mixture and engine revolutions per minute are presented in Table 1.

The analysis of the results, visualized in Fig. 3, allows to draw the following conclusions:

- CO_2 concentrations are lowest (1.5 to 3.2%) at values of the air-fuel ratio in the range of 17:1 to 20:1 and engine speed in the range of 800-1200 rpm;
- CO_2 content is highest (4.5 to 5.5%) at the air-fuel ratio in the range of 10:1 to 14:1 and engine speed in the range of 1400-1800 rpm;

Correlation and regression analyses were used to process the results, aiming at describe the relationships between the investigated emissions and engine properties. The correlations values prove a strong dependence between the ratio of the air-fuel mixture and the measured CO_2 values at 1000 rpm, 1200 rpm and 1400 rpm ($p<0.05$). Fig. 4, 5 and 6 show the regression equations and their coefficients depending on the changes of studied parameters. It is obvious that the changes of the AFR could explain more than 50% of the observed reduction in CO_2 emissions ($R^2 = 0.51\text{-}0.64$).

Table 1. CO_2 emissions (%) depending on the values of the Air Fuel Ratio and engine speed (rpm).

CO_2 (%)		Engine speed (rpm)						
		800	1000	1200	1400	1600	1800	2000
Air-fuel mixture ratio	10:1	2.80	3.53	4.25	5.00	5.32	5.40	4.47
	11:1	2.14	3.72	3.99	4.80	5.36	5.41	4.74
	12:1	2.20	3.82	3.48	4.81	5.39	5.42	4.70
	13:1	1.97	3.43	3.40	4.78	5.31	5.43	4.70
	14:1	2.33	3.56	3.33	4.85	5.46	5.51	4.70
	15:1	1.69	3.72	3.43	4.80	5.36	5.56	4.70
	16:1	2.02	3.66	3.11	4.68	5.35	5.57	4.68
	17:1	1.84	3.23	3.32	4.65	5.35	5.53	4.68
	18:1	1.52	3.22	3.22	4.67	5.36	5.58	4.64
	19:1	2.10	3.17	3.20	3.84	5.29	5.60	4.59
	20:1	1.80	3.15	3.48	3.96	5.34	4.66	4.70

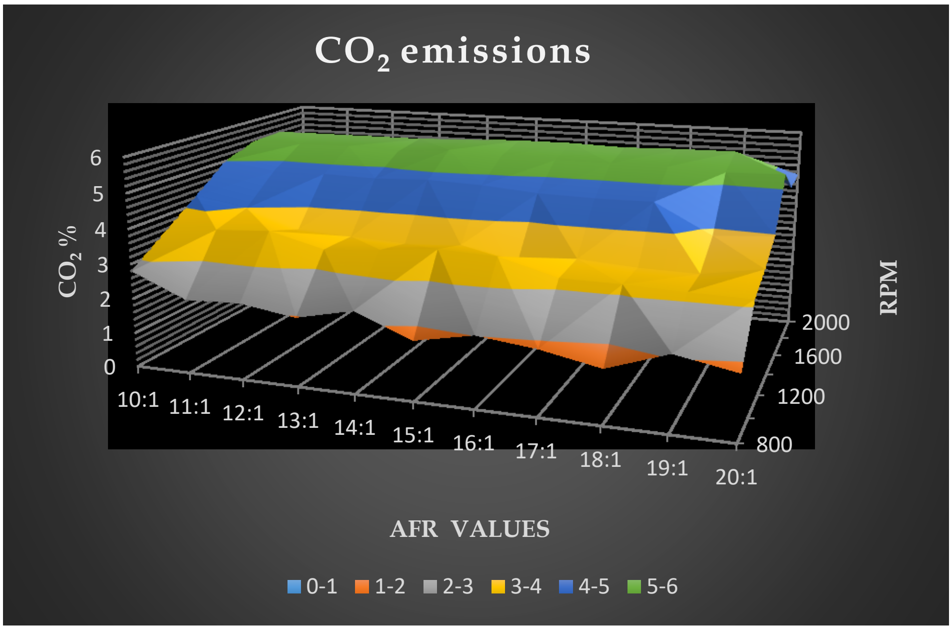

Fig. 3. Diagram of CO_2 changes depending on the different Air Fuel Ratio (AFR) and different engine speeds (rpm).

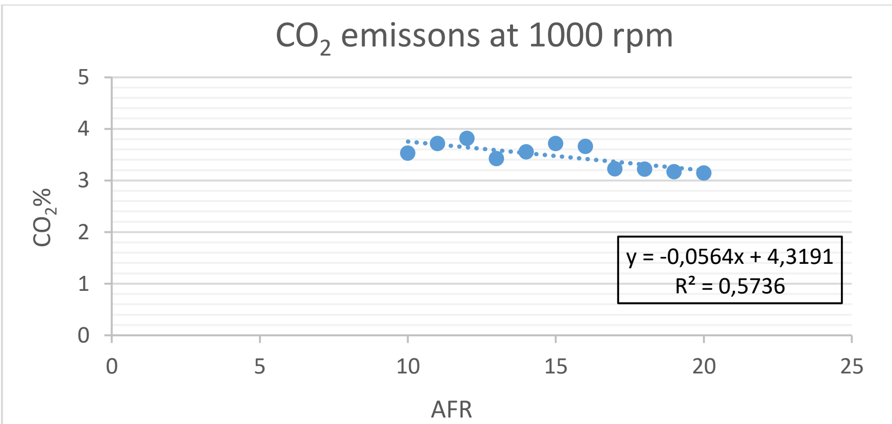

Fig. 4. Linear regression between CO_2 content and different Air Fuel Ratio at 1000 rpm.

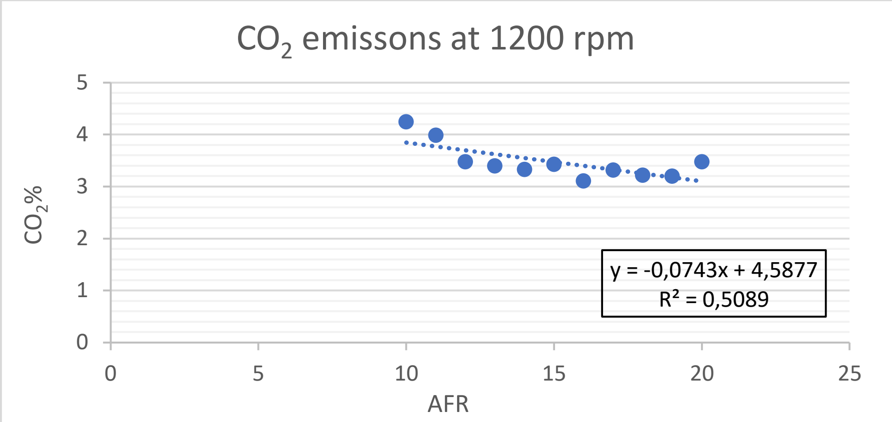

Fig. 5. Linear regression between CO_2 content and different Air Fuel Ratio at 1200 rpm.

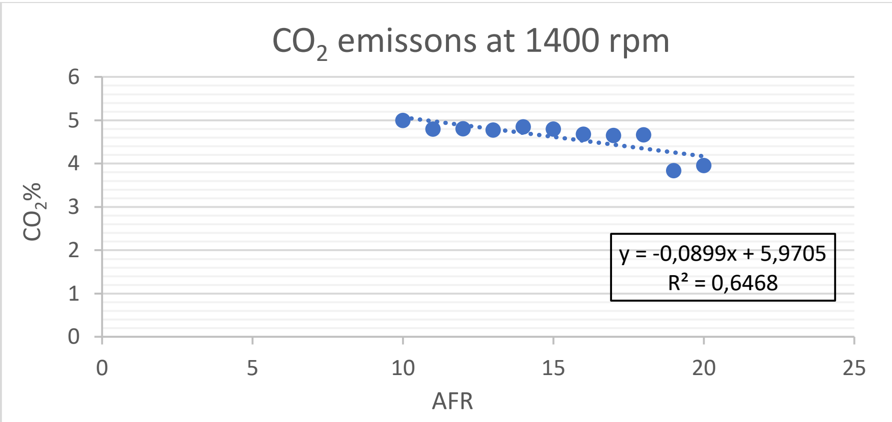

Fig. 6. Linear regression between CO_2 content and different Air Fuel Ratio at 1400 rpm.

Average values of the unburned hydrocarbons (HC) concentration depending on air-fuel ratio and engine speed are presented in Table 2.

The analysis of the results, visualized in Fig. 7, revealed at the following conclusions:

- HC emissions are lowest (3399 to 3997 ppm) at AFR values in the range of 14:1 to 18:1 and engine speed in the range of 1000-1200 rpm;
- HC emissions are highest (5170 to 5313 ppm) at the air-fuel mixture ratio in the range of 17:1 to 20:1 and engine speed in the range of 1600-1800 rpm;

Also evident from the results is the fact that with a richer mixture, the HC levels drop at higher engine revolutions, which is also based on the greater velocity of the exhaust gases.

The values of the correlation coefficients prove a strong dependence between the ratio of the air-fuel mixture and the measured values of HC at 1800 rpm and 1600 rpm, medium dependence at 1000 rpm and 1200 rpm, as well as a weak dependence at 800 and 1400 rpm ($p<0.05$).

Linear regression equations were used to process the results, through which the regression coefficients of the studied HC emissions were obtained (Fig. 8, 9 and 10). It can be seen that the AFR values are the main factor determining the HC content of the exhaust gases. The effect is more pronounced at higher engine speed (1800 rpm) where the R^2 =0.9248, which means that the 92.5% of the total variance of the studied variable (HC emissions) could be explained by the changes of the studied factor (AFR). The influence of air-fuel ratio on the harmful HC emissions is obvious also at 1000 rpm and 1600 rpm, where R^2 values are 0.7513 and 0.6467 respectively.

The presence of unburned hydrocarbons in engine exhaust is of particular interest to the automotive industry for two reasons. The first one is the air pollution, especially in terms of smog formation. The second one is related to fuel conservation, namely the kilometers per litter (miles per gallon) to be gained by utilizing the chemical energy of exhaust gas hydrocarbons.

Table 2. HC emissions (ppm) depending on the Air Fuel Ratio and engine speed (rpm).

HC		Engine speed (rpm)						
		800	1000	1200	1400	1600	1800	2000
Air-fuel mixture ratio	10:1	4098	3449	3875	4321	4416	4966	4061
	11:1	4506	3661	3950	4461	4813	5041	4824
	12:1	4409	3718	3501	4431	5011	5113	4809
	13:1	4598	3815	3663	4402	4942	5122	4796
	14:1	4397	3812	3563	4500	5163	5170	4806
	15:1	4638	3745	3500	4513	5144	5218	4794
	16:1	4715	3788	3409	4371	5184	5223	4785
	17:1	4715	3856	3474	4431	5184	5200	4756
	18:1	4747	3997	3458	4516	5190	5257	4701
	19:1	4728	3942	3399	3653	5169	5303	4641
	20:1	4152	3909	3688	3854	5218	5313	4795

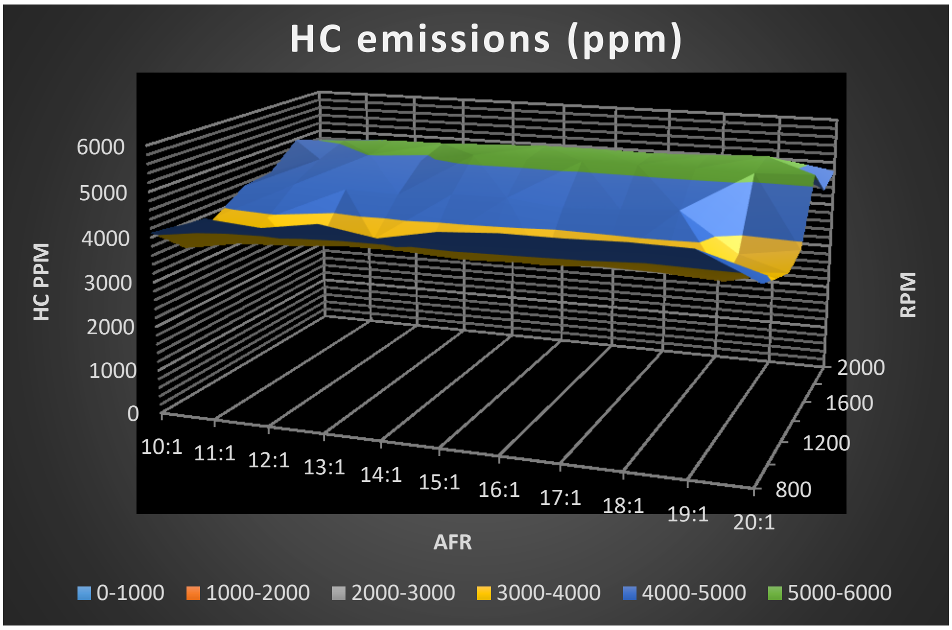

Fig. 7. Diagram of hydrocarbons (HC) changes depending on the different Air Fuel Ratio (AFR) and different engine speeds (rpm).

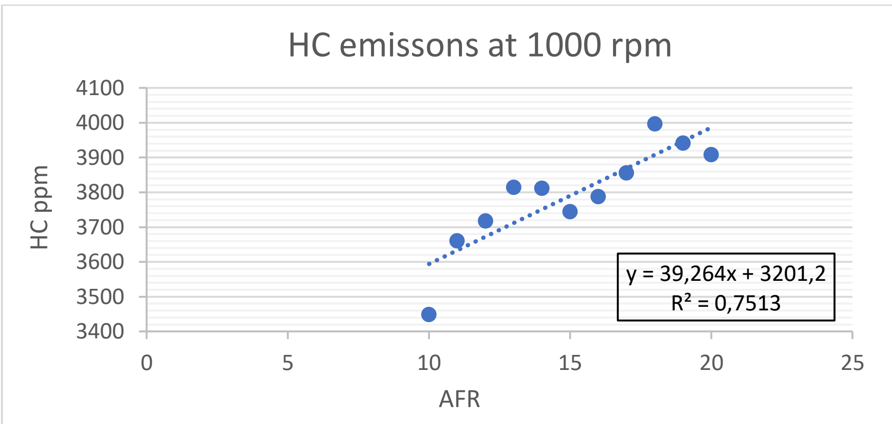

Fig. 8. Linear regression between unburned HC content and different Air Fuel Ratio at 1000 rpm.

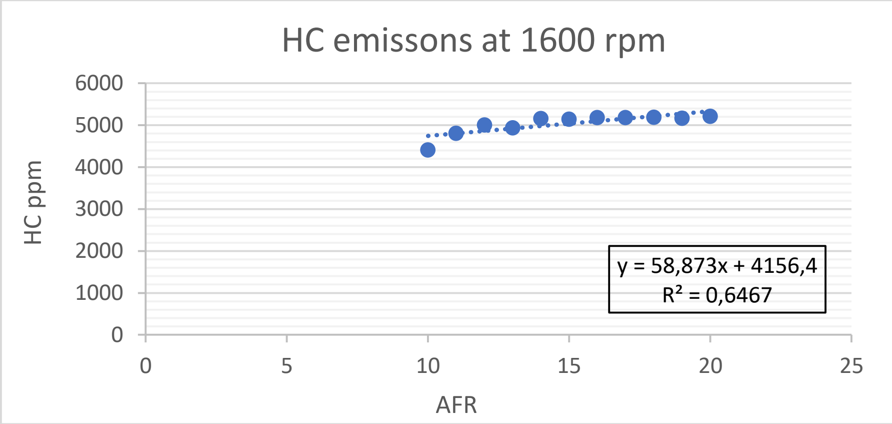

Fig. 9. Linear regression between unburned HC content and different Air Fuel Ratio at 1600 rpm.

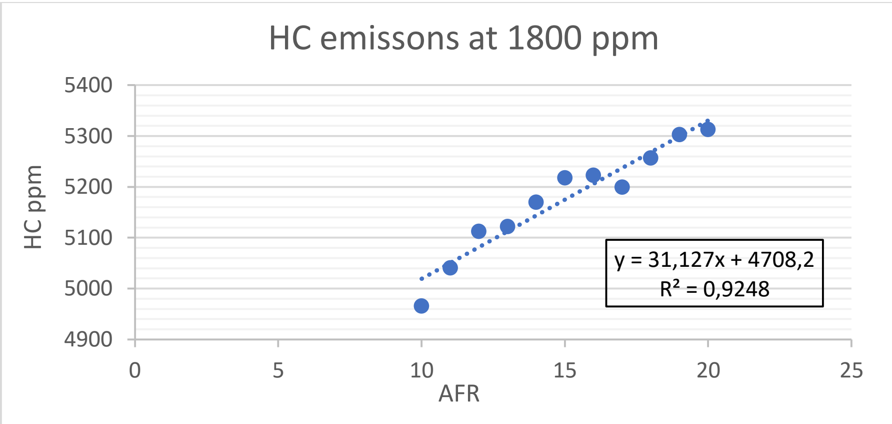

Fig. 10. Linear regression between unburned HC content and different Air Fuel Ratio at 1800 rpm.

The average results of the measurements conducted on the carbon monoxide (CO) changes depending on the values of the air-fuel ratio and the engine revolutions per minute are presented in Table 3.

The analysis of the results visualized in Fig. 11, gives us a reason to draw the following conclusions:

- CO values are the lowest (0.01 to 0.1%) at the air-fuel mixture ratio in the range of 16:1 to 20:1 and engine speed in the range of 800-1400 rpm,
- CO values are highest (0.56 to 0.61%) at the fuel-air mixture ratio in the range of 10:1 to 11:1 and 1800 rpm engine speed, as well as at the AFR in the range of 16:1 to 19:1 and 1600 rpm engine speed.

Visible from the results and the diagram is the pronounced CO emission at 1800 engine rpm and air-fuel ratio in the range of 10:1 to 14:1 and the subsequent decrease in CO with increasing engine speed and fuel-air enrichment mixture.

The values of the correlation coefficients prove a significant dependence between the air-fuel ratio values and the measured CO values.

Linear regression equations were used to process the results, through which the regression coefficients of the studied emissions (Fig. 12, 13 and 14). The strongest impact on the CO content in exhaust gases was observed at engine speed of 1800 rpm where the changes in the air-fuel ratio resulted in almost 95% of the total variance of the studied parameter. Significant relationships between CO emissions and AFR was found also at the 1600 rpm and 1000 rpm, as the coefficient R^2 values explained more than 65% of the variance in the studied parameter.

It is well known that higher levels of CO generally occur in areas with heavy traffic congestion and it can cause harmful health effects even on healthy people by reducing oxygen delivery to the body's organs and tissues. That is why all potential options to decrease the CO emissions are of a particular interest.

Table 3. CO emissions (%) depending on the Air Fuel Ratio and engine speed (rpm).

CO (%)		Engine rpm						
		800	1000	1200	1400	1600	1800	2000
Air-fuel mixture ratio	10:1	0.07	0.09	0.03	0.08	0.07	0.61	0.14
	11:1	0.07	0.09	0.01	0.07	0.21	0.56	0.12
	12:1	0.03	0.08	0.08	0.06	0.22	0.55	0.10
	13:1	0.03	0.09	0.09	0.05	0.43	0.48	0.10
	14:1	0.02	0.09	0.09	0.06	0.52	0.46	0.10
	15:1	0.01	0.08	0.09	0.50	0.50	0.41	0.11
	16:1	0.02	0.08	0.06	0.06	0.61	0.42	0.11
	17:1	0.01	0.08	0.05	0.03	0.56	0.33	0.09
	18:1	0.01	0.08	0.05	0.03	0.56	0.34	0.09
	19:1	0.00	0.07	0.04	0.13	0.55	0.32	0.11
	20:1	0.07	0.06	0.03	0.08	0.51	0.32	0.09

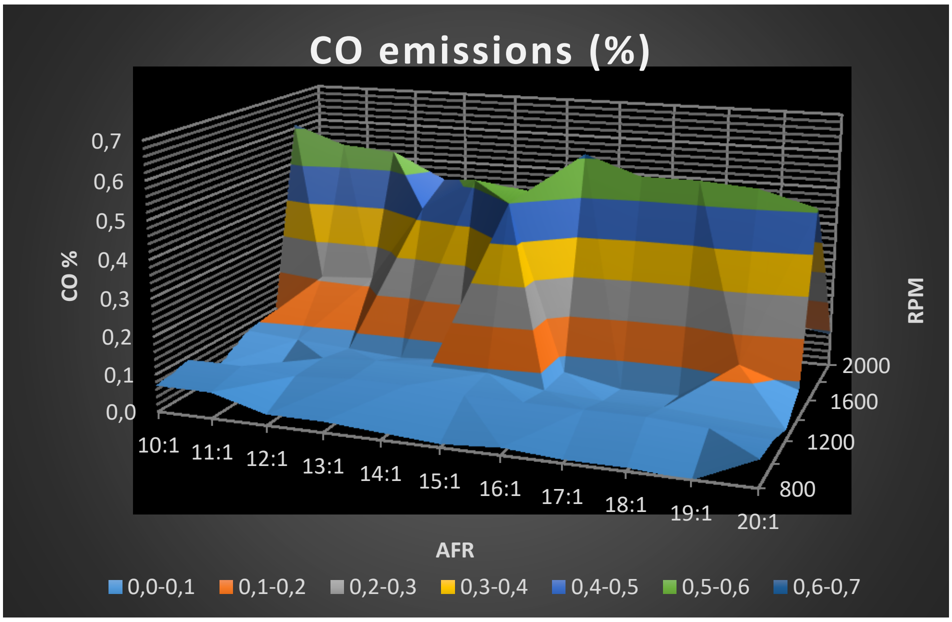

Fig. 11. Diagram of carbon monoxide (CO) changes depending on the different Air Fuel Ratio (AFR) and different engine speeds (rpm).

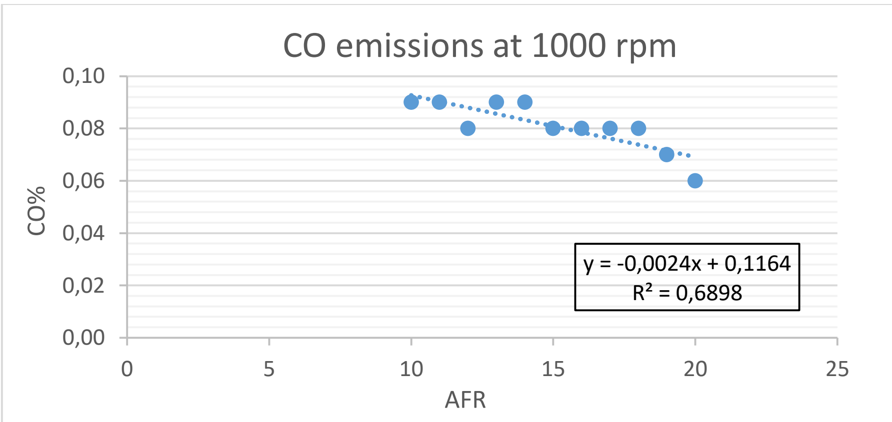

Fig. 12. Linear regression between CO content and different Air Fuel Ratio at 1000 rpm.

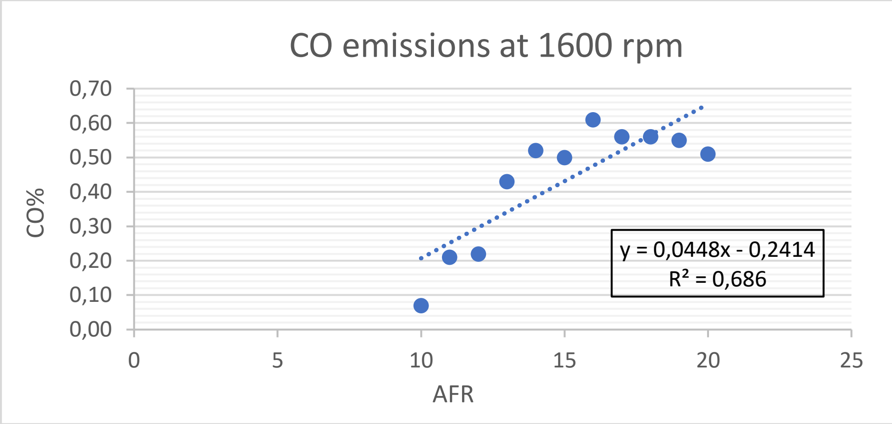

Fig. 13. Linear regression between CO content and different Air Fuel Ratio at 1600 rpm.

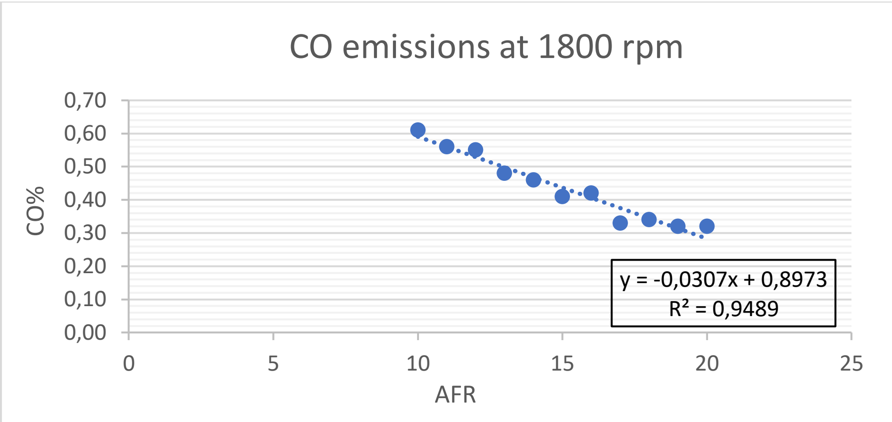

Fig. 14. Linear regression between CO content and different Air Fuel Ratio at 1800 rpm.

Conclusions

Based on the emissions measurements and analyses performed, we would like to recommend for the implementation of dynamic operating modes and fuel maps for the engines in order to reduce harmful emissions in different driving modes.

The present study should alert the specialists working in the automotive industry to direct their expert potential to the optimization of the fuel-air mixture ratio of gasoline engines with internal combustion.

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