

AN ANALYSIS OF SIGNIFICANCE LEVEL OF RELATION BETWEEN AMBIENT TEMPERATURE AND EXHAUST EMISSION IN THE INITIAL TERM OF SI ENGINE'S WORK

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Summary. The presented paper introduces problems concerned with exhaust emission, produced at the work of a combustion engine fed with petrol in unstable thermal conditions after a cold starting in low temperature. The aim of the paper is to estimate the significance level of the relation between the ambient temperature in which the starting takes place and the emission of the chosen fumes components. The analysis has been taken using standard statistic tools and the results of that are next presented and they show that predicted relations really exist.

Key words: exhaust gas emission, cold start, starting temperature, SI engine.

INTRODUCTION

Nowadays, both the obliging regulations and the ones predicted to be in force within the next few years, concerning the environment protection, [Bielaczyc 1999] face the combustion engines with higher and higher requirements. The tests' procedures will much more widely treat the character of the whole process of an engine's exploitation as well as an influence of separate phases of the exploitation upon the toxic emission levels.

An engine's starting and the next period of warming up are now enclosed in the tests which are currently in use. However, the newest trends in the directives are to state the procedures including measurements for a lower engine's starting temperature shortening the period between the starting and the beginning of driving [Romaniszyn 2008].

The initial period of a SI engine's work after its cold starting is especially significant in view of carbon monoxide (CO), hydrocarbons (HC) and nitrate oxides (NO_x) emission levels. [Bielaczyc 1998, 2000, Kuranc 2005, 2008].

An engine's starting and the next phase of not thermally stabilised work is bound up with several disadvantages effects which impact upon the combustion process [Mysłowski 1996, Kilar 2000]. One of the most important is the lack of possibility to create proper air-fuel mixture, caused

among others by side wall and slit effects, which make the fuel evaporate and poorly mix with air. It is also connected with flame extinction next to the “cold” cylinder wall. Moreover, the catalytic converter is not working efficiently in that period [Kojtych 2001, Merksiz & others 2005]. After a cold engine’s start up the inner converter’s temperature is more or less equal to the ambient temperature. Therefore, the carbon monoxide (CO) and hydrocarbons (HC) oxidation in the converter goes poorly, too and the emission is relatively high [Kowalewicz 1994].

In order to obtain an unfailing ignition and a stable engine’s work for a proper vehicle’s driving, the start up fuel dose, enriching the mixture, is to be applied. It takes effects in larger fuel consumption and a higher CO₂ and other toxins’ emission levels. Larger amount of sprayed fuel within the starting conditions is to recompense for the weaker evaporating, but at the same time it results in incomplete combustion leading to undesirable emissions [Kuranc 2002].

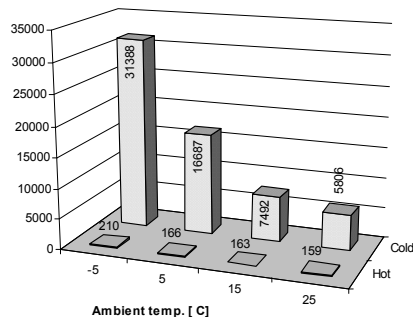
AIM AND RANGE OF RESEARCH

The research was undertaken to obtain information concerning the connection between the ambient temperature and the chosen fume compounds’ emission levels in the initial period of work. In conjecture that the connection exists, the significance level estimation of the mentioned relation was undertaken.

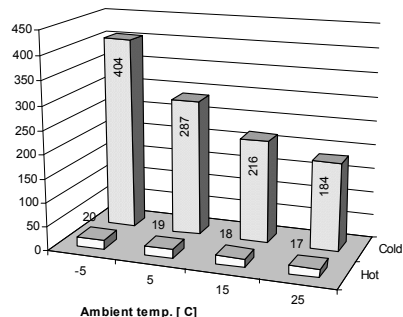
METHODOLOGY

The investigations were carried upon the passenger car equipped with electronically steered SI MPI engine GA16DE of the Nissan make with the capacity of 1596 cm³ and maximum output power of 73 kW. In the measurements the 488A Plus infrared type gas analyzer was used [Kuranc 2006]. A single measurement took several minutes respectively to the observed changes of the considered values. Volumetric concentrations of CO, HC, CO₂, and NO_x were recorded among other parameters. The engine worked with automatically regulated shaft’s speed without outer external loading. The procedure was repeated a few times for each of the chosen ambient temperature values (−5°C, +5°C, +15°C, +25°C) [Kuranc 2005].

a). CO Emission [Nm³ · 10⁻⁶]



b). HC Emission [Nm³ · 10⁻⁶]



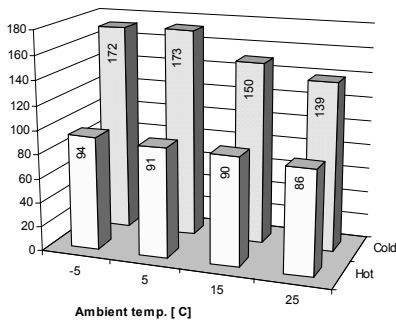
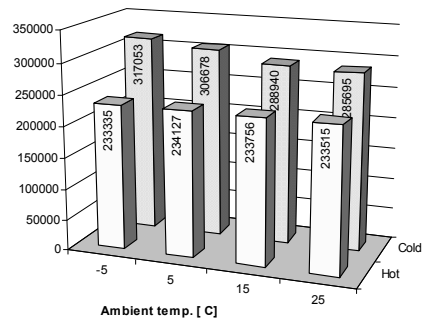
c). NO_x Emission [$\text{Nm}^3 \cdot 10^{-6}$]d). CO_2 Emission [$\text{Nm}^3 \cdot 10^{-6}$]

Fig. 1. Total emission of CO, HC, NO_x and CO_2 within 800 s of idling after the cold and hot starts at different ambient temperatures

ANALYSIS OF SIGNIFICANCE LEVEL OF RELATION BETWEEN AMBIENT TEMPERATURE AND EXHAUST EMISSION DURING START-UP AND WARM-UP

The relation between the ambient temperature and exhaust emission was estimated on the basis of particular components' emissions within the period of 800 seconds after the engine's start. Comparison was taken upon groups of results measured for four air temperature levels. It was to be checked whether the mean values of the emission significantly differ from each other with regard to the measurement's temperature, or the differences are not meaningful.

To compare several means, more than two, the proper statistical analysis is the analysis of variance, abbreviated as ANOVA. If the hypothesis about equality of means is rejected the question arises, which means differ from the others [Dietrich & Schulze 2000]. To answer this question the multiple comparison tests can be done. One of the best is the Tukey multiple comparison test, called Tukey HSD (honestly significant differences), which controls the overall significance level for all the compared pairs of means.

It should be noticed, that ANOVA procedure can be applied only if the following assumptions are fulfilled:

- errors are independent and normally distributed,
- variances of errors are equal (homogenous).

The assumption of normality can be evaluated by means of the so-called normal probability plot for residuals or a test for normality, for example Shapiro-Wilk's test. It is considered that ANOVA is quite robust against the assumption of normality. The assumption of homogeneity of variances can be checked by many tests, for example Bartlett's or Levene's test. Generally, this assumption is also not vital for ANOVA. The more dangerous situation, which can result in misleading results, is the presence of a correlation between means and variances in groups [STATISTICA 1997, Koronacki & Mielniczuk 2001, Wawrzosek 2006]. This situation can be diagnosed by the plot means versus variances.

There are two ways of treating data when the assumptions of ANOVA are seriously violated. The first one is using the nonparametric Kruskal-Wallis test, which do not need any assumptions about normality and equality of variances. The other way is trying to transform the data so that the

transformed one fulfils the assumptions. The most common transformations, which can improve normality or homogeneity of variances are logarithm and square root.

The way of treating the data in this paper is as follows:

1. If the assumptions of ANOVA are fulfilled we use ANOVA, where the treatment (temperature) has got four levels (-5°C , $+5^{\circ}\text{C}$, $+15^{\circ}\text{C}$, $+25^{\circ}\text{C}$). If the hypothesis of the lack of differences is rejected (p -value less than 0.05) then we use Tukey test to detect which differences are statistically significant.

2. If assumptions of ANOVA are not fulfilled then we try to transform the data. If the aim is reached then we use ANOVA as in the step 1.

3. If the transformation does not improve normality and homogeneity of variances then we perform nonparametric Kruskal-Wallis test. If the hypothesis about the lack of differences between groups is rejected then we perform nonparametric Mann-Whitney test to check which groups differ from the others.

RELATION BETWEEN EMISSION AND COLD START TEMPERATURE

Carbon Monoxide

In this case the variances in groups are not homogenous. There is also a correlation between means and variances in groups. Thus the logarithm transformation was applied to the data and it gave expected results. For transformed data p -value in Bartlett test is ≈ 0.477 , in Levene test ≈ 0.405 . The correlation between means and variances also disappeared and normal probability plot for residuals does not point at abnormality. Results of ANOVA for the transformed data are given in Table 1 and they point out at a significant influence of temperature on the emission.

Table 1. The ANOVA table for the logarithm of CO emission

Degrees of freedom for temperature	MSA	Degrees of freedom for errors	MSE	F	p-value
3	3.56642	20	0.00676	527.6114	$3.37 \cdot 10^{-19}$

Next, the Tukey test shows significant differences in emissions between all the considered temperatures, which is also noticeable when watching the mean values. The lower temperature causes the higher emission levels (Fig. 2.a).

Table 2. The Tukey table for the CO emission

	{1}	{2}	{3}	{4}
Means after the transformation	10.3511	9.7221	8.9198	8.6617
-5°C {1}		0.000175*	0.000175*	0.000175*
$+5^{\circ}\text{C}$ {2}	0.000175*		0.000175*	0.000175*
$+15^{\circ}\text{C}$ {3}	0.000175*	0.000175*		0.000299*
$+25^{\circ}\text{C}$ {4}	0.000175*	0.000175*	0.000299*	

* – differences significant at level of 0.05

All the values showed in Table 2. are lower than 0.05 so in each case the differences are significant (at the significance level of 0.05).

Hydrocarbons

In case of HC the data were also transformed via logarithm and then ANOVA was applied. Similarly as in the case of CO for HC (Table 3) it was noticed that emissions seriously depend on ambient temperature.

Table 3. The ANOVA table for the logarithm of HC emission

Degrees of freedom for temperature	MSA	Degrees of freedom for errors	MSE	F	p-value
3	0.713765	20	0.003001	237.8291	$8.3 \cdot 10^{-16}$

Applying the Tukey multiple comparison test it can be observed that all the analysed differences are significant. The analysis proves analogous to CO and visible at first sight in the means (Fig. 2.b) character of dependence HC emission on the cold start temperature. It confirms the tendency: the lower the temperature, the higher the emission of HC is.

Table 4. The Tukey table for the HC emission

	{1}	{2}	{3}	{4}
Means after the transformation	5.999885	5.657458	5.374460	5.214355
-5°C {1}		0.000175*	0.000175*	0.000175*
+5°C {2}	0.000175*		0.000175*	0.000175*
+15°C {3}	0.000175*	0.000175*		0.00047*
+25°C {4}	0.000175*	0.000175*	0.00047*	

* – differences significant at level of 0.05

Nitrate Oxides

When analysing nitrate oxides' emission there was no need to apply the logarithm transformation to the data because the hypothesis of homogeneity of variances had not been rejected and it was also found that the differences for the temperatures were significant (Table 5).

Table 5. The ANOVA table for the NO_x emission

Degrees of freedom for temperature	MSA	Degrees of freedom for errors	MSE	F	p-value
3	1362.455	20	85.46593	15.9415	$1.57 \cdot 10^{-5}$

Table 6. The Tukey table for the NO_x emission

		{1}	{2}	{3}	{4}
Means		172.0000	173.0011	150.0025	143.6070
−5°C	{1}		0.99763	0.002859*	0.000337*
+5°C	{2}	0.99763		0.001914*	0.000281*
+15°C	{3}	0.002859*	0.001914*		0.63506
+25°C	{4}	0.000337*	0.000281*	0.63506	

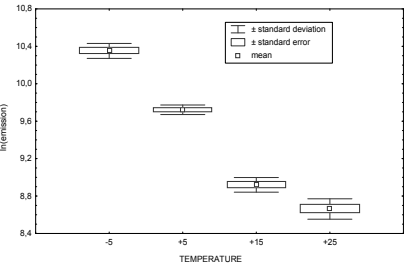
* – differences significant at level of 0.05

However, not all the values (Table 6) were less than 0.05, so the differences were not significant in each case. The Tukey multiple comparison test showed that:

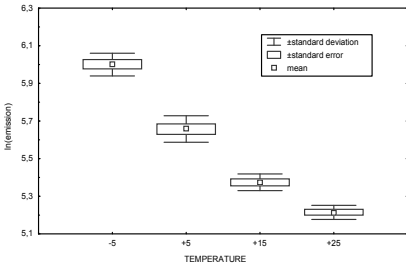
- the emissions in the cold start temperatures −5°C and +5°C are not significantly different,
- the emissions in the cold start temperatures +15°C and +25°C are not significantly different,
- the emissions in temperatures −5°C and +5°C are significantly higher than emissions in temperatures +15°C and +25°C.

Carbon Dioxide

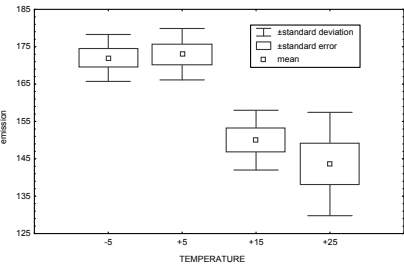
The most difficult was the analysis concerning CO₂. The data did not fulfil the ANOVA requirements, because of different variances in groups, not proper normal probability plot and correlation between means and standard deviations in groups. Unfortunately, the logarithm or square transformation did not help. In such situation the nonparametric Kruskal-Wallis test was applied and it showed significant differences in emissions in the considered starting temperatures (p-value 0.0002).



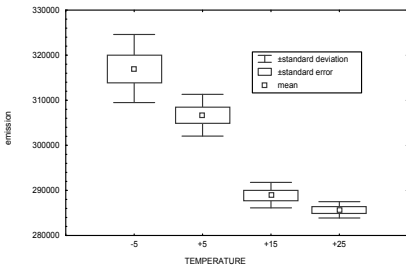
a). logarithm of CO emission



b). logarithm of HC emission



c). emission of NO_x



d). emission of CO₂

Fig. 2. The boxes and the whiskers plots for the concerned values according to the cold starts

To check which groups of emissions differ significantly from the others, the nonparametric Mann-Whitney test was performed and it showed that:

- the emission in the cold start temperature -5°C is significantly higher than in temp $+5^{\circ}\text{C}$,
- the emission in the cold start temperature $+5^{\circ}\text{C}$ is significantly higher than in temp $+15^{\circ}\text{C}$,
- the emissions in temperatures $+15^{\circ}\text{C}$ and $+25^{\circ}\text{C}$ are not significantly different at the significant level 0.05 (Table 7).

Table 7. The Mann-Whitney test table for the CO_2 emission

Differences	between -5°C and $+5^{\circ}\text{C}$	between $+5^{\circ}\text{C}$ and $+15^{\circ}\text{C}$	between $+15^{\circ}\text{C}$ and $+25^{\circ}\text{C}$
p-values	0.025	0.004	0.055

Some kind of supplement, added to this part of the article, may be the information presented in Fig. 2. in which we can see mean values, standard deviations and errors for the analysed values concerning the cold start.

RELATION BETWEEN EMISSIONS AND AMBIENT TEMPERATURE AT HOT STARTS

Using the same statistical methods as mentioned in the previous chapter, a comparison of differences of the emissions at hot starts and 800 seconds of idling at ambient conditions (same as at the cold starts) were made.

Carbon Monoxide

The data was transformed (natural logarithm) and then ANOVA was applied, which confirmed the significance of the differences between the emissions of CO in different temperatures (Table 8).

Table 8. The ANOVA table for the logarithm of CO emission – hot start

Degrees of freedom for temperature	MSA	Degrees of freedom for errors	MSE	F	p-value
3	0.095993	20	0.024772	3.875036	0.024641

Applying the Tukey multiple comparison test it was found out that the only significant differences (at level 0.05) were between the emission in temperature -5°C and $+25^{\circ}\text{C}$. The other differences were insignificant.

Hydrocarbons

The analysis of variance did not show statistically significant influence of the ambient temperature on the hydrocarbons' emission (Table 9).

Table 9. The ANOVA table for the emission of HC – hot start

Degrees of freedom for temperature	MSA	Degrees of freedom for errors	MSE	F	p-value
3	7.076313	20	7.970457	0.887818	0.464365

Nitrate Oxides

The analysis of variance did not show statistically significant influence of the ambient temperature on the nitrate oxides' emission (Table 10).

Table 9. The ANOVA table for the emission of HC – hot start

Degrees of freedom for temperature	MSA	Degrees of freedom for errors	MSE	F	p-value
3	68.691	20	253.99	0.270448	0.84594

Carbon Dioxide

Because the data did not fulfill the ANOVA requirements and the transformations did not eliminat that problem, the nonparametric Kruskal-Wallis test was applied, but it did not prove significant connection between the emissions and the temperature.

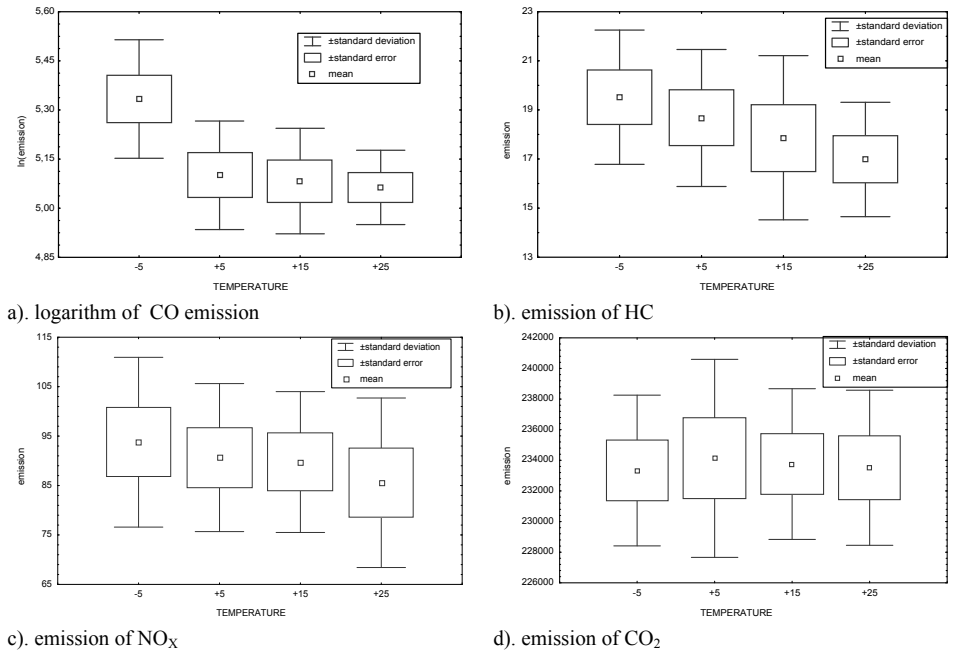


Fig. 3. The box-and-whiskers plots for the concerned values according to the hot starts

FINAL CONCLUSIONS

On the basis of the realised research and statistical analysis, supported by theoretical knowledge one can formulate the following conclusions:

1. The levels of CO and HC emissions at an engine's cold start and during its warming rise while the ambient temperature lowers. One can notice that:

a). the value of total emission of CO, observed within 800 seconds after the cold start in the temperature of -5°C is, correspondingly, 1.9; 4.2 and 5.5 times greater than in the cases of cold starts in the temperatures of $+5^{\circ}\text{C}$, $+15^{\circ}\text{C}$ and $+25^{\circ}\text{C}$; similarly the emission of HC observed at -5°C is equal to 140% of emission observed for the temp. $+5^{\circ}\text{C}$, 187% of emission at $+15^{\circ}\text{C}$ and ca. 220% of emission at $+25^{\circ}\text{C}$.

b). the statistical analysis showed that the emission of the detrimental compounds (CO, HC, NO_x and CO_2) significantly depends on temperature, at which the engine starts.

2. Lowering the cold start's temperature seriously affects, through higher fuel consumption, the warming up period, which can be seen through the higher emission of CO_2 .

3. An influence of the ambient temperature upon the emission at the hot starts is observed, but it is not important as for its value when compared to the cold start. A significant connection between the emission and the ambient temperature is observed only in the case of carbon monoxide. The only important difference is between the temperatures -5°C and $+25^{\circ}\text{C}$. The cause of that situation is due to high values of variances in groups.

4. The emissions of detrimental fume compounds during cold start and warming the SI engine are in each presented case several times higher than the emissions from the hot engine in the same ambient conditions.

Recapitulating the analysis of the presented results and formulated conclusions, which confirm advisability of undertaking that subject, it should be stressed that the initial period of work after the cold start of a combustion engine must not be neglected in the general analysis of an influence of motorization upon the environment.

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ANALIZA ISTOTNOŚCI ZWIĄZKU TEMPERATURY OTOCZENIA Z EMISJĄ SPALIN W POCZĄTKOWYM OKRESIE PRACY SILNIKA O ZI

Streszczenie. W zaprezentowanym artykule opisano wyniki badań emisji wybranych składników spalin silnika zasilanego benzyną, wyposażonego w katalityczny układ oczyszczania spalin. Badania realizowano podczas początkowego okresu pracy silnika po uruchomieniu w temperaturze otoczenia. Celem pracy jest ocena związku poziomu emisji wybranych składników spalin z temperaturą otoczenia, w której następuje rozruch silnika. Analizę istotności związku temperatury i emisji podjęto przy pomocy typowych narzędzi statystycznych. Wyniki tych prac zostały zaprezentowane i wskazują na występowanie przewidywanych zależności w przypadku kilku spośród analizowanych składników spalin.

Słowa kluczowe: silnik spalinowy, zimny rozruch, gorący rozruch, emisja spalin, szkodliwe składniki spalin.