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A METHOD OF ENGINES' DIAGNOSIS IN OPERATION

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Abstract

It was found that there are discrepancies between the values of diagnostic parameters obtained in the test and natural exploitation. In addition, no appropriate tests are carried out which would be based on the degree of engine degradation in long-term natural use. One of the reasons is the lack of adequate, non-invasive diagnostic methods. The aim of the work was to show the possibility of creating a new diagnostic parameter of combustion engines in their natural operation. The parameter can be determined by a new method (presented in the article). The method is based on the assumption that the technical condition of the engine can be judged on the basis of the run-up curve, and in particular, on the basis of the linear direction coefficient, which is approximated by the points of the run-up curve at particular moments of the run-up. An additional requirement is that the points of the run-up curve are the average value of the speed from many runs. In addition, the statistical distributions of the speed values in the individual moments of the run-up should be of the same type. The direction coefficient of the straight line determined is a diagnostic parameter. The value of the new coefficient is the value of the straight-line factor. Further works are underway to determine the relationship between the directional coefficient and the technical condition of the engine.

Keywords: *transport, combustion engine, engine diagnostic, diagnostic methods, engine technical conditions*

1. Introduction

Despite the relatively dynamic development of electric vehicles (BEV) it is anticipated that motor vehicles (ICEV), especially hybrid ones (ICHV), for a long time will be the basis of motorization.

Emissions from internal combustion engines are limited both in terms of quantity (by limiting carbon dioxide emissions – Fig. 1.) and qualitatively (by reducing the concentration of toxic components in exhaust gases (e.g. in Europe, the current EURO 6 standard is applicable) [7, 8, 9].

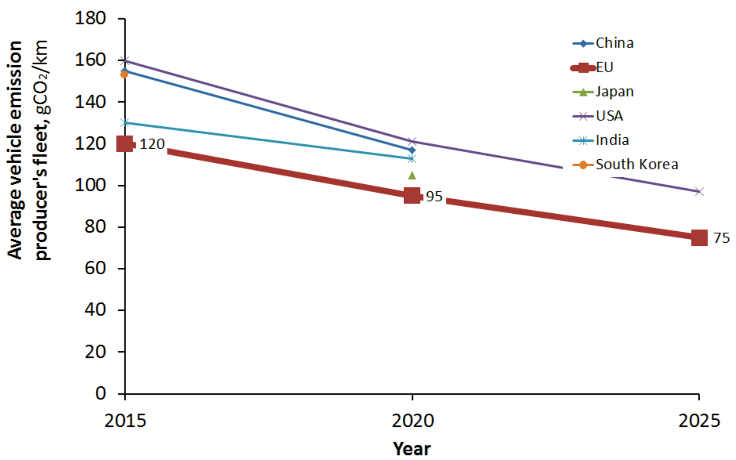

Fig. 1. Forecasted limitations on the emission of vehicle fleets marketed in the coming years

Meeting the requirements of standards is increasingly difficult. Comprehensive vehicle tests, including stand tests, are required. The tests can be classified as braking and operating tests.

Examinations in dyno tests do not give any certainty that good results obtained in tests will also occur in natural service conditions. It is observed that the progress shown in research tests (NEDC, FTP, etc.) is not reflected in natural exploitation [1-5, 12] – Fig. 2.

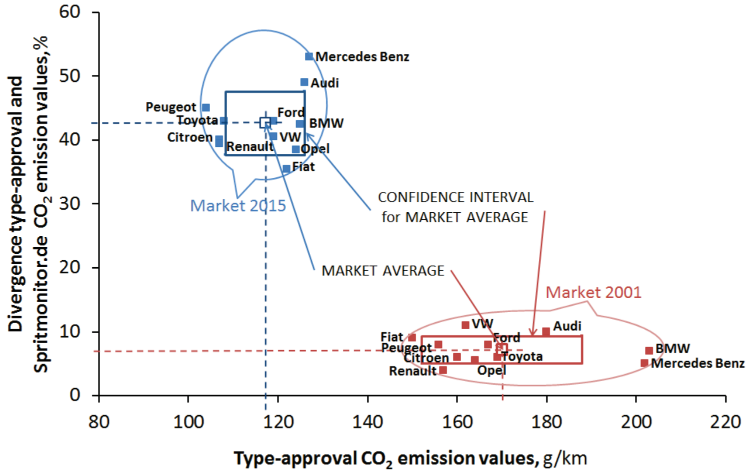

Fig. 2. Divergence type-approval and Spritmonitor.de CO_2 emission values as function of type-approval CO_2 emission values depending of the time

The reasons for this state of affairs are seen, among others in "mismatch" of test conditions to real ones. It is expected that this problem will disappear as the WLTP (Worldwide harmonized Light vehicles Test Procedure) has been in force since September last year (2017). Vehicles are degraded during natural operation. The slow degradation process obviously affects engine emissions – usually unfavorably. In addition, e.g. in [2] it was found that "Routine idle emission tests are not taken into account" [11].

A method of assessing the technical condition of the engine during its operation is necessary. Of course, it would be best if it was a non-invasive method, and at the same time it would be possible to evaluate each engine's copy. A proposal for the assumptions of such a method is presented in this article.

2. Method assumptions

It has been assumed that conditions suitable for engine testing in operation will be the conditions of its free run-up. The measurement does not require any interference in the structure of the vehicle and can be carried out at any time.

The internal combustion engine, as a simple system, is shown in Fig. 3.

The engine is supplied with energy $\boldsymbol{E}(t)$ and external loads $\boldsymbol{M}(t)$. The engine is characterized by a set of its features, but these features change slowly during operation – as a function of the service life time t_e of these. The object's response to the forced and changed characteristics is the rotation of the crankshaft $\omega(t)$ and the emissions expressed by the concentration of each component of the exhaust gases $\boldsymbol{K}(t)$.

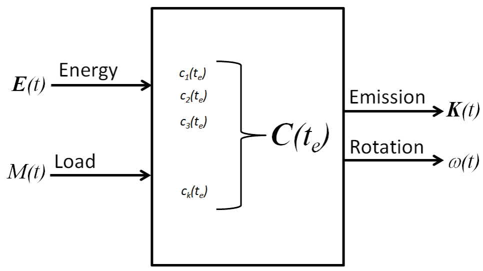

Fig. 3. Engine in a simplified system approach

Because, by definition

$$t_e \gg t\,, \qquad t_e = \{t\}, \tag{1}$$

the time t_e can be treated as long-term (mileage) while time t can be described as temporary. In turn, time t_e is a set of moments t. It follows that when analyzing a system in time t, it is analyzed simultaneously at the given time (especially in one of the moments constituting the set $\{t\} = t_e$).

System analysis can be carried out by using a mathematical model. The mathematical model is a set containing extortion, features, object responses and relationships between them, therefore it is a set

$$\{\boldsymbol{E}(t), M(t), \boldsymbol{C}(t_e), \boldsymbol{K}(t), \omega(t), \boldsymbol{R}\}, \quad t_e = \{t\}, \tag{2}$$

The problem is therefore not only to determine the values of particular quantities in the model but also to determine the set of $\boldsymbol{R}$ relations, whereby:

$\boldsymbol{E}(t)$ – ccollection of energy flows,
$\boldsymbol{M}(t)$ – a set of loads,
$\boldsymbol{C}(t)$ – a set of object features,
$\boldsymbol{K}(t)$ – a collection of exhaust components (their concentration),
$\boldsymbol{R}$ – collection of relations,
$\omega(t)$ – angular speed of the engine crankshaft,
t_e – operating time,
t – time (temporary).

$\boldsymbol{R}$ relationships can be divided into two main groups; relations regarding static conditions and relations regarding dynamic conditions. This distinction is relatively easy if we assume that relations regarding static conditions are appropriate to the case when the derivative of particular quantities related to time is equal to zero in at least several consecutive moments, while dynamic conditions occur in the remaining cases.

From the entire spectrum of the $\boldsymbol{R}$ relationship, in the further part of the publication, selected issues regarding the specific situation of the so-called engine run-up [6]. The $\boldsymbol{R}$ set will be limited to practically one R-element that captures the change in rotational speed of the crankshaft of the engine running without an external load caused by a step increase in energy supplied to the engine.

If:

$$\Delta E_k > 0, \tag{3}$$

this increase in kinetic energy can be recorded as:

$$\Delta E_k = \Delta\frac{I\omega^2}{2} = I\frac{(\omega_2^2-\omega_1^2)}{2}. \tag{4}$$

The elementary kinetic energy gain can be written as dE_k. If this increment occurs in dt time, it can be saved:

$$\frac{dE_k}{dt} = I\frac{d\frac{\omega^2}{2}}{dt} = I\omega = L. \tag{5}$$

That is, the supply of energy causes the momentum momentum L. The momentum of momentum can change over time:

$$\frac{dL}{dt} = I\frac{d\omega}{dt} = I\varepsilon = \sum M_j = M_i(t) - M_{il}(t) - M_r(t), \tag{6}$$

where:

I – mass moment of inertia of moving parts of the engine brought to the axis of the crankshaft,
ε – angular acceleration of the engine crankshaft,
$M_i(t)$ – indicated torque,
M_{il}(t) – the torque of internal losses,
$M_r(t)$ – external torque loading the engine.

Time in the above dependencies is treated as:

$$t_{e2} - t_{e1} = \Delta t_{e1} = t \rightarrow 0, \tag{7}$$

therefore, if (in at least several consecutive moments):

$$M_i(t) = M_{il}(t) + M_r(t). \tag{8}$$

This:

$$\frac{d\omega}{dt} = 0 \rightarrow \omega = const, \tag{9}$$

which means that the engine is running at a constant speed.

In all other cases, the torque balance is disturbed and the engine runs at variable speed. If the time difference is over then:

$$t_{e2} - t_{e1} = \Delta t. \tag{10}$$

Providing energy to the engine will increase the kinetic energy of the moving parts, but only when it simultaneously exists:

$$M_i(\Delta t) > M_{il}(\Delta t) + M_r(\Delta t). \tag{11}$$

And you can save (using the second principle of dynamics) that:

$$\sum M_j = M_i(\Delta t) - M_{il}(\Delta t) + M_r(\Delta t) = I(\Delta t)\frac{\Delta\omega}{\Delta t}. \tag{12}$$

The introduction of energy to the engine must cause a change in the speed of its crankshaft – which is obvious because engines are used for this. However, on the other hand, the principle of dynamics does not indicate how this change will take place in time Δt, or how a function looks like:

$$\omega = \omega(t). \tag{13}$$

Equation (12) also has a second factor, which is the moment of inertia I. If the engine components were not subject to degradation processes, one could assume that the moment of inertia of the engine with the assumed structure is constant. However, as the engines run, the degradation processes are progressing. Maybe it does not matter for the size of rotating masses (losses of mass of elements due to their degradation are on the order of 10^{-6} and should not have a significant effect on the reduced moment of inertia, however, no more important is the occurrence of bigger clearances, and this may already significantly affect the thermodynamic cycle of the engine (compression pressures achieved) and thus the acceleration of the angular velocity, and therefore also the course of the function $\omega(t)$.

It was therefore assumed that:

$$\omega(t) \leftrightarrow TCE, \tag{14}$$

where:
TCE – technical condition of the engine.

Because the engine speed is based on the concept of rotational speed expressed in revolutions per minute, which is related to the angular velocity through the relationship:

$$\omega = \frac{\pi n}{30}, \tag{15}$$

it was further assumed that:

$$TCE \leftrightarrow n(t). \tag{16}$$

The main problem dealt with in the work presented in this publication was to explain how to determine the line of the course during the engine speed during its run-up, i.e. $n(t)$.

3. Investigations

The medium-sized diesel engine was mounted on a dynamometer station. The necessary media has been delivered to the engine. The engine was not connected to the brake. A rotational speed sensor was mounted on the crankshaft axis and correlated with the time measurement unit. A special driver system was built to increase the dose of fuel by leaps and bounds [10]. Fig. 4 illustrates the fuel dose rate (red) and the corresponding engine crankshaft speed (blue).

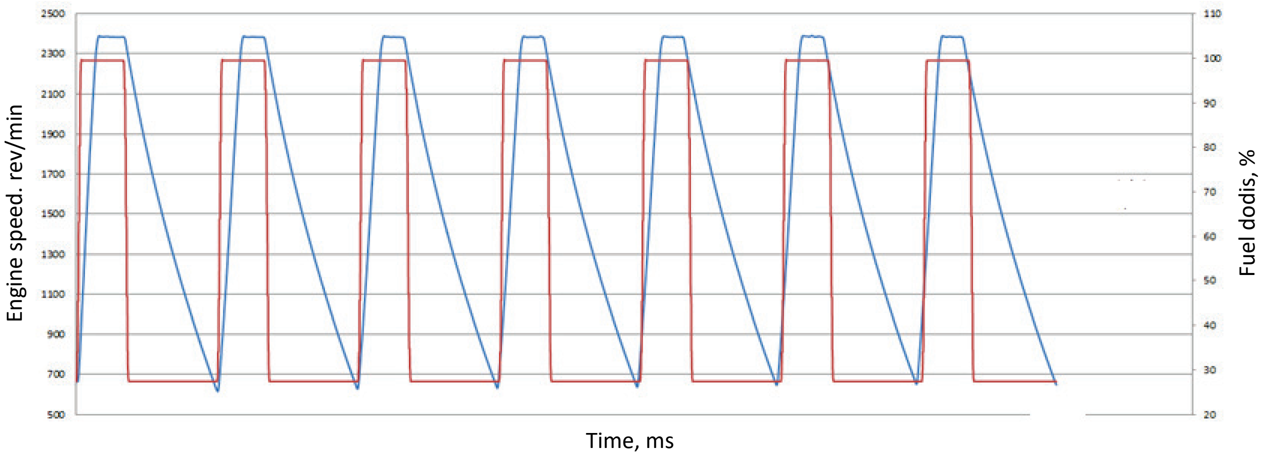

Fig. 4. The course of fuel dose and engine speed during measurements

The rapid increase in the fuel dose results in acceleration of the engine (from idling speed to maximum crankshaft speed.) A drop in the fuel dose results in a slow decreasing of the rotational speed from maximum to idle speed, which was repeated (in the example analyzed here) 30 times.

4. Measurement results

The sample results are shown in Fig. 5. (tables with measurement results are the responsibility of the authors and are not included here due to the limitation of the volume of publication).

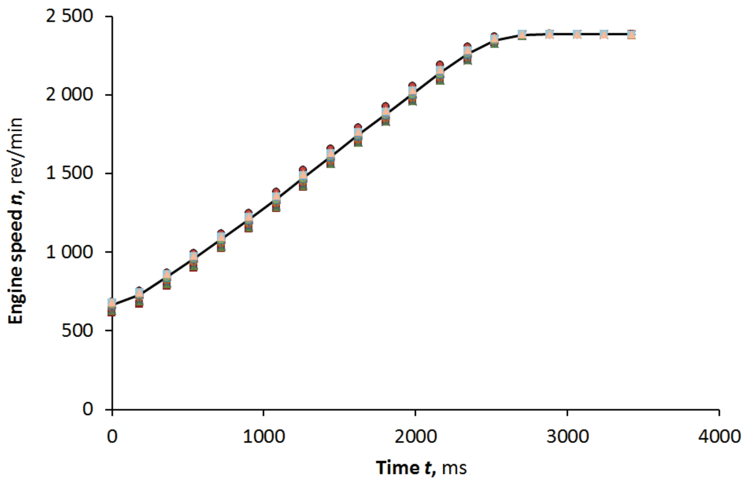

Fig. 5. The recorded values and the course of the average engine speed values in relation to the time of acceleration (run-up) of the engine

The figure shows that the run-up speed at each of its moments differs. After statistical analysis of the 30 values corresponding to the particular moments of the inrush, the average run and run-up speed were determined as well as the confidence interval for this mean – Fig. 6.

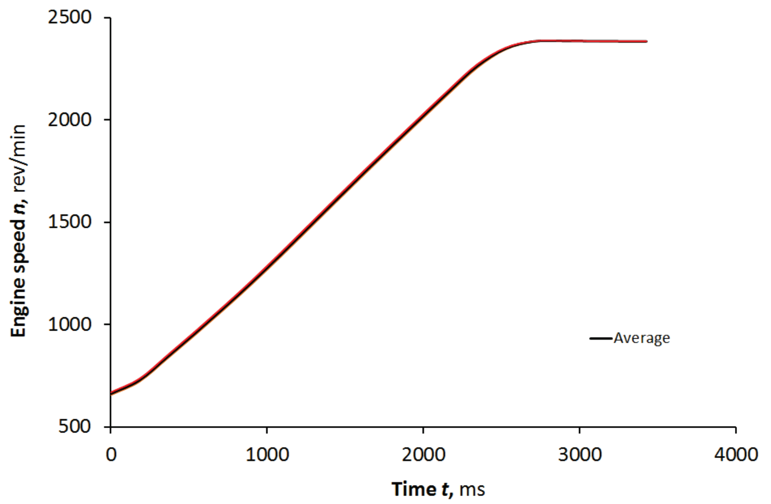

Fig. 6. The course of the mean value (with its confidence interval) of the engine speed during its run-up

The next step was to check whether the distribution of the speed values is the same at particular moments of the run-up. Fig. 7 shows that the speed distribution of the run-up in the initial and final moments thereof may be statistically different as in the intermediate moments closer to the center of the run-up time.

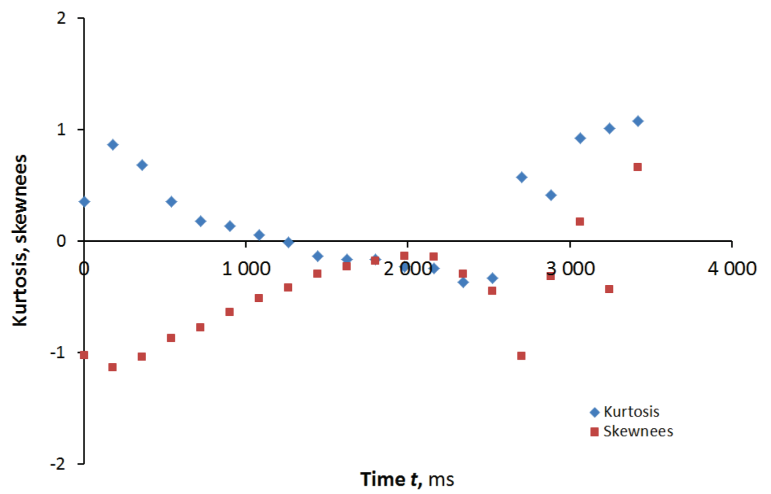

Fig. 7. Kurtosis I skewness of speed distribution in particular moments of the run-up

It was assumed that the speed of 30 engine runs at individual moments can be described by a normal distribution. To verify the assumption, the values of the Shapiro-Wilk test were calculated [8]. The Shapiro-Wilk test statistic value is given the following formula:

$$W = \frac{\left[\sum_{i=1}^{\left[\frac{n}{2}\right]} a_{n-i+1}(x_{n-1+1} - x_i)\right]^2}{\sum_{i=1}^{n}(x_i - x_{śr})^2}, \tag{17}$$

where:

n – number of samples,
$[n/2]$ – the total part of the number $n/2$,
x_i – variable that accepts the i-th largest value in the sample,
a_{n-i+1} – fixed Shapiro-Wilk coefficients,
also:

– the variable W is assuming the truth of the zero hypothesis of the Shapiro-Wilk distribution,
– the test rejection area is in the interval [0; Wcr],

– *Wcr* can be read from the table and depends on the assumed level of significance,
– a significance level of $\alpha = 0.05$ was assumed for which, given a number of 30 samples, $Wc = 0.928$.

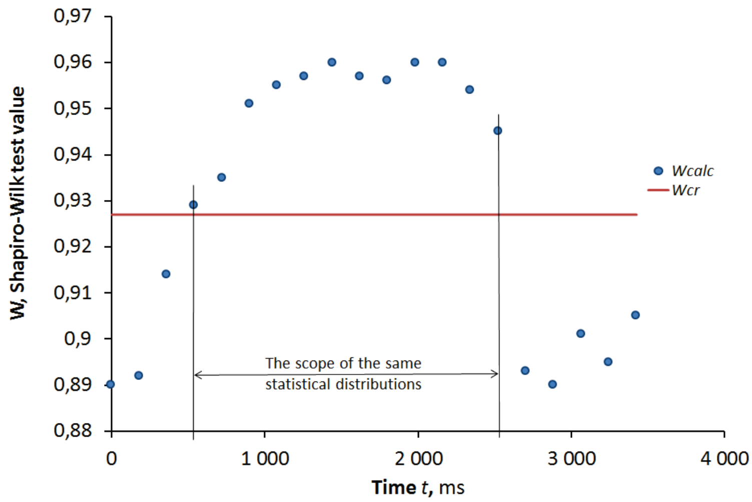

Fig. 8. Values of the Shapiro-Wilk distribution statistics in particular times of the run-up

The *Wcr* value for the normal distribution should be outside the range [0, 0.928]. As can be seen in the range of 540-2523 ms, distributions are normal. In this time range, the average speed was approximated by a straight line – Fig. 9. This line can be written as:

$$APR = b_o + b_1 t = 568 + 0.72t. \tag{18}$$

The model's correlation coefficient (18) has the *RSQR* value = 0.999074, so it is very high.

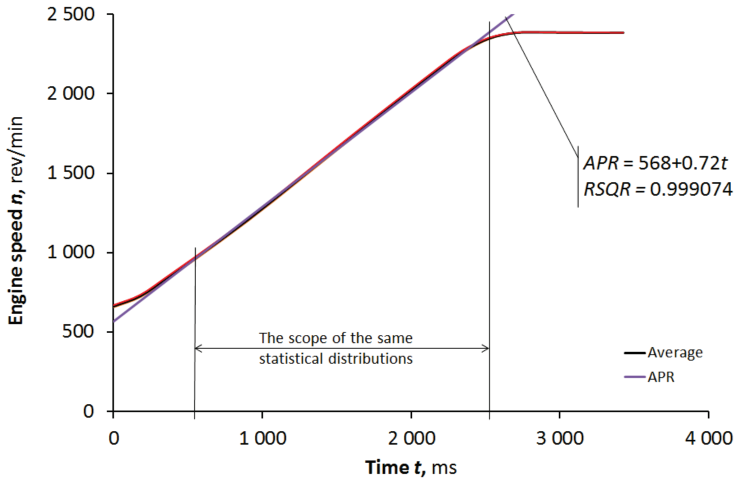

Fig. 9. Average speed curve of the run-up and a simple approximation of its values described by normal distribution

For diagnostic purposes, the slope of the *APR* line is important. The slope tangent of this line is equal to $b_1 = 0.72$ (in this particular case). It is expected that the values of this parameter will change with the time of use (and the specific type and engine copy). Research to confirm this observation is underway.

5. Conclusions

The aim of the work was to show the possibility of creating a new diagnostic parameter of combustion engines in their natural operation – it seems that the goal has been achieved. The parameter can be determined by a new method (presented in the article). The method is based on the assumption that the technical condition of the engine can be judged on the basis of the run-up curve, and in particular on the basis of the linear direction coefficient, which is approximated by the points of the run-up curve at particular moments of the run-up. An additional requirement is that the points of the run-up curve are the average value of the speed from many runs. In addition, the statistical distributions of the speed values in the individual moments of the run-up should be of the same type. The direction coefficient of the straight line determined is a diagnostic parameter. The value of the new coefficient is the value of the straight line factor. Further works are underway to determine the relationship between the directional coefficient and the technical condition of the engine.

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