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CONCEPT AND MODELS FOR EVALUATION OF BLACK AND WHITE SMOKE COMPONENTS IN DIESEL ENGINE EXHAUST

Summary. A method for measuring exhaust smoke opacity has been developed, which allows estimating the differentiated components forming black exhaust and those forming white smoke. The method is based on video recording and special software for processing the video recording data. The flow of the diesel exhaust gas is visualised using the digital camera, against the background of the screen, on a cut of an exhaust pipe, and with sufficient illumination of the area. The screen represents standards of whiteness and blackness. The content of the black components (soot) is determined by the degree of blackening of the white standard in the frames of the video, and the content of whitish components (unburned fuel and oil, etc.) is determined by the degree of whitening of black standard on the frames of the video. The paper describes the principle and the results of testing the proposed method of measuring exhaust smoke opacity. We present an algorithm for the frame-by-frame analysis of the video sequence, and static and dynamic mathematical models of exhaust opacity, measured under free-acceleration of a diesel engine.

1. INTRODUCTION

Diesel engine design improvement, which enabled its better competitiveness against gasoline engines in terms of exhaust gas toxicity levels, noise emission, specific power, and other consumer characteristics resulted in the substantial expansion of its application in motorway transport. Consequently, the share of the atmospheric air emissions of the diesel engines' pollutants increased, which, in turn, results in the need to arrange efficient status monitoring of the vehicles equipped with compression ignition engines.

A large number of researchers are engaged in issues related to improvement of work processes and control of diesel exhaust [1-9].

Currently, the exhaust gas toxicity of the diesel engine vehicles in operation is evaluated by consolidated parameters – exhaust gas (EG) smoke represented by the optical absorption coefficient *K*, m^{-1} or light attenuation coefficient: *N*, % [10]. To evaluate diesel engine EG smoke instruments one of two measurement methods may be used.

The *optical method* is based on the evaluation of the exhaust gases' absorption of light at a certain wavelength (in the visible spectrum). This measurement method commonly referred to as the Hartridge method is defined by international standards (UNECE Rules No. 24, ISO-3173/ ISO 11614) and provides the use of neutral light filters certified for light transmission factor as reference elements for instrument calibration and verification. This method is generally acknowledged and widely used in the design of industrial instruments to monitor motor vehicles' EG smoke in operation. However, the method has a certain disadvantage consisting in the fact that the instrument photocell responds not only to the soot in the exhaust gases but also to the water steam and other whitish components of the exhaust gas, which contribute to its opacity.

The *filtration method* (referred to in the industry as Bosch method) is based on the evaluation of the degree of blackening of the white filter paper during the pumping of the set volume of the exhaust gases through it. This method applied reference samples of different blackness degrees – from white to black. However, it found no mass-scale application for the following reasons: the measurement process is split into two stages (sampling and element blackness measurement); special elements (filtering paper) are required for measurement purposes; the gas volume in each measurement must be constant. Among the disadvantages we may also mention the fact that this method does not enable splitting the EG stream into different components (whitish and black) contributing to its opacity.

It is also worth mentioning that the standardized EG smoke indicator (*K; N*) provides only generalized engine process flow quality evaluation without breaking down the EG into components. Consequently, the overall smoke indicator is of limited information value for the evaluation of the diesel engine's technical status. Breakdown of the overall EG smoke indicator into components would enhance the information value of the diesel engine diagnosis process.

2. THE SUGGESTED METHOD FOR THE EVALUATION OF THE VISIBLE EXHAUST IN DIESEL ENGINE EXHAUST GASES

Transport department of Siberian Federal University developed a method for EG smoke measurement based on artificial vision elements, which enables splitting the EG stream into components contributing to the EG blackness and those producing the EG whiteness [11]. The method consists in the following provisions:

1. The video of the diesel engine emission is taken against the background of the reference screen with adequate illumination. Here, the video recorder and screen are fixed (fig. 1). The screen being the reference for whiteness and blackness is required to identify both dark components in the EG (black smoke on the white background) and presence of the light components (whitish smoke on the black background).

At the method approbation stage [12, 13] a black-and-white striped paper sheet (fig. 2) was used as the reference screen. However, later, this type of screen was rejected because of the fact that in the total illumination of over 2000 lux the black stripes whitened (became grey) and had measured blackness of about 70–75 %.

Whiteness and blackness reference standards provided in fig. 3 were used instead.

The whiteness reference standard was represented as the white sheet of paper fixed on the rigid base with the embedded blackness reference standard. The blackness reference standard was represented by the cylinder plugged on one side (diameter 50 mm, length – 250 mm) painted with black matte paint inside. Besides, because of the fact that there is no natural source of light inside the pipe and the external light sources emitting direct light rays are on a different elevation and are not reflected from the pipe's bottom, the measured blackness on the cut is close to 100 % (i.e., we have an approximated model of the "absolutely black body").

2. The video obtained using a dedicated computer program is split into maximum possible number of frames–images (fig. 4) – as per the shooting speed.
3. On each frame from the video shot certain scenes are selected – in the immediate vicinity of the cut exhaust pipe (fig. 5). The selection of the scenes is defined by a number of factors: first, the farther the smoke is from the exhaust pipe, the more intense the vapor formation is, which brings about the error; second, the longer the distance from the exhaust pipe edge, the stronger is the variation and uncertainty of the layer of the gas in question.
4. Then, by matching the reference images the degree of the color parameters are determined (using RGB scale from 0 to 255: R – red; G – green; B – blue) for the scenes from each frame compared with the initial scenes taken in the video without exhaust gases. The color values obtained are converted into brightness values using one of the equations known in digital telemetry [14]:

$$L = (0{,}212671 \cdot Red + 0{,}715160 \cdot Green + 0{,}072169 \cdot Blue), \quad (1)$$

where *L* is brightness; Red is red color numerical value; Green is green color numerical value; Blue is blue color numerical value.

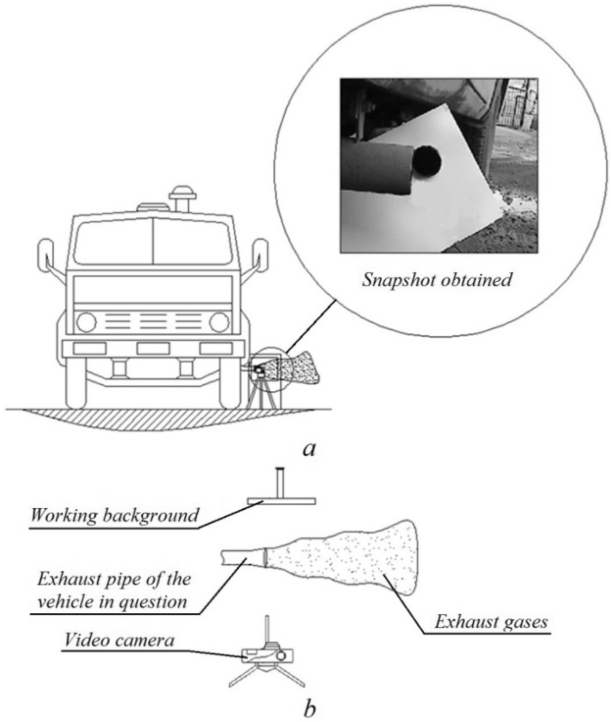

Fig. 1. Layout of the instruments during the measurement of the EG smoke: *a* – front view; *b* – top view

Fig. 2. Reference screen used at the fine-tuning stage

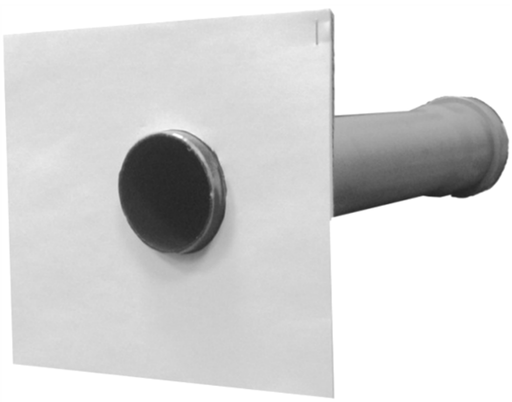

Fig. 3. Suggested whiteness and blackness reference standards

Fig. 4. A sequence of frames

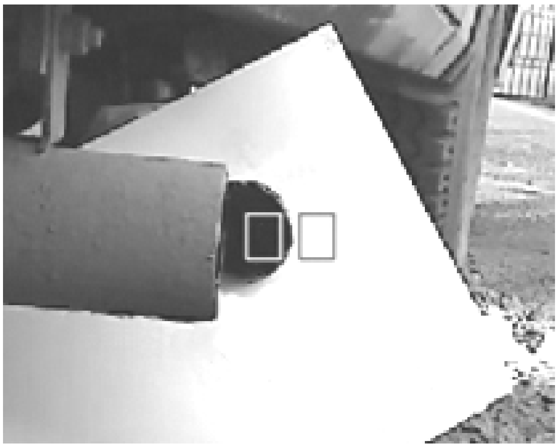

Fig. 5. Selection of scenes on the frame

At each stage of the method fine-tuning the procedure for evaluation of color parameters was conducted in manual mode by comparing the overall brightness of the scenes with virtual reference samples.

In automatic mode it proved to be more convenient to evaluate the frame brightness by determining the pixel brightness on an RGB scale followed by the calculation as per equation (1). The pixel color may be determined using built-in tools of the standard image-processing software.

5. The value obtained using two components – "black on the white background" and "white on the black background" – is converted into the light attenuation coefficient *N* (opacity) using the set linear function:

$$N = 1{,}015 \cdot L - 1{,}280, \quad (2)$$

where *N* is the light attenuation coefficient, %; *L* is measured brightness of the selected scenes.

Equation (2) was determined experimentally. The study object was represented by a set of neutral color filters (NCF) as the EG physical analogs. The research conducted and its review demonstrates that the dependence of the opacity and blackness of the neutral color filters (2) measured using standardized software is linear in nature with the determination coefficient, R^2, close to one: i.e., this dependence may be identified as being functional and close to a linear one.

Therefore, the EG images are used to determine the *N* indicator obtained with the smoke column thickness equal to the diameter of the exhaust pipe edge diameter.

6. Because of the fact that the standards strictly identify the smoke meter effective base equal to 0.43 m, the evaluation obtained for each scene must be normalized to the standardized thickness of the smoke column.

It is known [10] that the optical absorption constant *K* and light attenuation coefficient *N* are logarithmically inter-related by the following equation

$$K = -\frac{1}{L} \cdot \ln\left(1 - \frac{N}{100}\right), \quad (3)$$

where *L* is is the smoke meter effective base, m.

Then, if we perform the conversions, the light attenuation coefficient, in %, is as follows:

$$N = 100 \cdot \left(1 - e^{-K \cdot L}\right), \quad (4)$$

Using equation (3) to calculate the specific indicator K on the thickness of the gas layer L, equal to the exhaust pipe edge diameter, and using the value obtained with the regulated value L = 0.43 m in equation (4), the value of N indicator normalized to the smoke meter effective length equal to 0.43 m may be calculated.

7. This procedure shall be applied to all frames obtained from the video sequence shot (i = 1, …, n – sequential number of the frame in the video sequence), and based on processing results the decision about EG smoke of the diesel engine in question is made.

The EG smoke calculation algorithm implemented using the method proposed is provided in fig. 6 where L_S is the reference standard brightness; L_{EGi} is EG brightness in the frame; $R_S G_S B_S$ is colors of the reference standards on RGB scale; $R_{EG} G_{EG} B_{EG}$ is EG color on RGB scale; L_i is total brightness in the frame; N_i is intermediate value light attenuation coefficient in the frame; N_{EG} is total light attenuation coefficient in the frame.

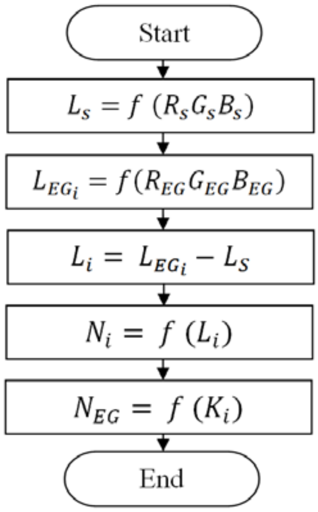

Fig. 6. Diesel Engine EG Smoke Calculation Algorithm

The processing algorithm was used for software enabling automatic processing of the video sequence taken. The recording device is represented as a web-camera transmitting the video in online mode; working with a prerecorded video file is also possible.

3. IMPLEMENTATION EXAMPLE

Examples of the data obtained from three free-acceleration cycles of Hyundai-County bus engine using the software and standardized calibrated smoke meter are provided in fig. 7 and 8, respectively. Peak values, stated in fig. 7, correspond to the maximum opacity values in two components ("black on the white" and "white on the black") obtained in the diesel engine free-acceleration cycles using the method proposed.

In fig. 8 peak values obtained in diesel engine free-acceleration cycles using a certified smoke meter correspond to the maximum opacity value.

The curves provided in fig. 7 and 8 demonstrate that the method proposed enables segregating the diesel engine's EG smoke into "black on white" (soot) and "white on black" (EG whiteness spots) components, which provides substantially more information of the quality of the work process flow in the engine.

Consequently, this information may be used for a more detailed evaluation of the diesel engine and its systems' technical status, which is rather topical for motor vehicles' operation.

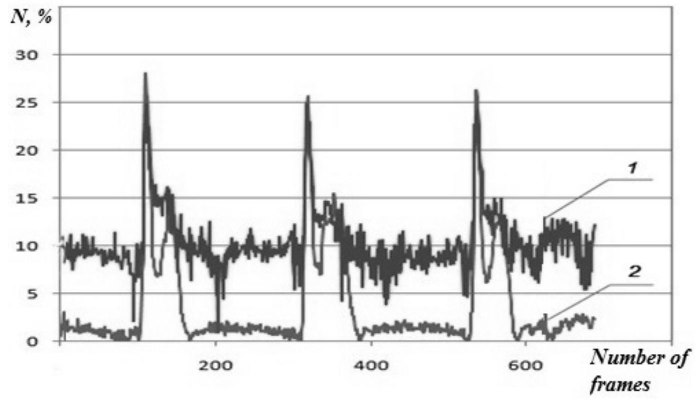

Fig. 7. Time sweeps obtained using the software: 1 – “black on the white” component; 2 – “white on the black” component

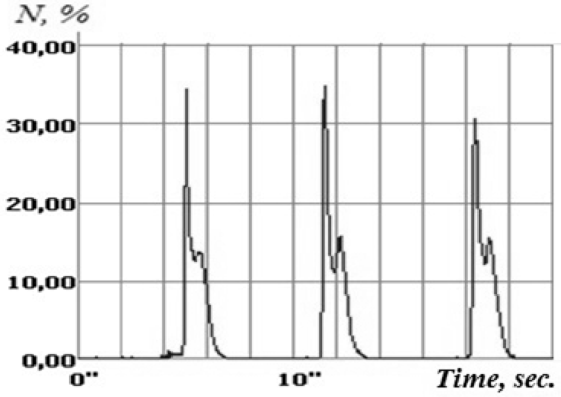

Fig. 8. Time sweep obtained using a conventional smoke meter

4. EG SMOKE MATHEMATICAL MODELS

To set the laws and nature of generation of black and whitish components during EG smoke monitoring in the diesel engine free-acceleration mode, experimental studies were conducted. On the basis of the fact that the issue of the percentage ratio making up “black on the white” and “white on the black” in the total value of the diesel engine EG smoke has not been studied in the technical literature so far, the authors attempted solve this problem using statistical methods. In type 1 statistical models the contribution of each component to the final value of smoke was determined based on the regression equation for different illumination modes.

For the type 1 model the following regression equation linking the factors in question was used:

$$D = a \cdot W + b \cdot B, \tag{5}$$

where D is the EG smoke recorded using a standard smoke meter, %; a and b are regression coefficients; W is “white on black” component value in total smoke, %; B is “black on white” component value in total smoke, %.

The research conducted demonstrated that the model quality is affected by the total illumination of the facility in question. The highest statistical parameters are observed in the models built on the illumination cases “everything in the light” and “everything in the shadow”, for which reason the practical implementation of the method it is appropriate for shooting the video in these illumination cases.

The final equation with the coefficients found for “everything in the light” case looks as follows:

$$D = 1{,}466 \cdot W + 0{,}670 \cdot B. \tag{6}$$

The final equation with the coefficients found for "everything in the shadow" case looks as follows:

$$D = 2{,}398 \cdot W + 1{,}485 \cdot B - 0{,}038 \cdot W \cdot B. \quad (7)$$

Here, the coefficients of determination have the following values: in the linear model $R^2 = 0.897$ and in the linear model adding the paired effect $R^2 = 0.936$. The calculation values of the Student criterion t: for the coefficient for W factor is from 18.29 to 35.15, and for the coefficient for B factor is from 14.31 to 31.43. The 95 % confidence interval in the linear model: with W factor is from 1.303 to 1.617; with B factor is from 0.582 to 0.767. The 95 % confidence interval in the model with pairing effect is: with W factor is from 2.189 to 2.449; with B factor is from 1.379 to 1.563; with WB factor *is* from –0.039 to –0.033.

In the second simulation case dynamic models are built for the difference equations using sequential linearization method. The dynamic models highlighting the nature of the generation (change) in the EG smoke as function of time in the free acceleration mode are built as function of the components considered. The best results were obtained for the difference model with two second-order inputs (input one – "white on the black" component $u(t)$, input two – "black on the white" component $u_1(t)$) and the order-four output (EG smoke $y(t)$).

$$y[t] = a_1 \cdot y[t-1] + a_2 \cdot y[t-2] + a_3 \cdot y[t-3] + a_4 \cdot y[t-4] + a_5 \cdot u[t-1] + a_6 \cdot u[t-2] + a_7 \cdot u_1[t-1] + a_8 \cdot u_1[t-2], \quad (8)$$
$$y[0] = y[-1] = y[-2] = y[-3] = 0,$$

where α_i is the vector of the model i^{th} parameter.

The sequential linearization method enabled identification of the EG smoke in free-acceleration mode in 4–5 iterations with a high accuracy. Examples of the resulting identification for one vehicle in different time intervals are provided in fig. 9.

Values of α_i coefficients in equation (8) found for different time intervals are provided in Tab. 1.

Table 1

Values of α_i Coefficients in equation (8)

α_i Coefficient	Values of α_i Coefficient for the Time Interval of	
	2 s	14 s
α_1	1.117775	1.0070797
α_2	0.0921513	0.0598842
α_3	–0.810551	–0.615632
α_4	0.4186891	0.2775199
α_5	0.1390694	0.2309282
α_6	–0.011012	–0.084602
α_7	1.0826057	1.0770474
α_8	–0.972921	–0.864093

5. CONCLUSION

The developed methodological approach and software enable solving the EG smoke problem and, consequently, determination of the diesel engine technical status by the EG flow color characteristics. The EG stream breakdown into blackness-forming and whiteness-forming components using the method proposed enables obtaining more information to evaluate the diesel engine technical status, enabling diagnosis reliability and cost reduction.

Equations obtained (6), (7), and (8) are characterized by the acceptable accuracy of the diesel engine technical status determination and enable highlighting the EG smoke generation as a function of time, both for a stand-alone measurement and for a group of measurements.

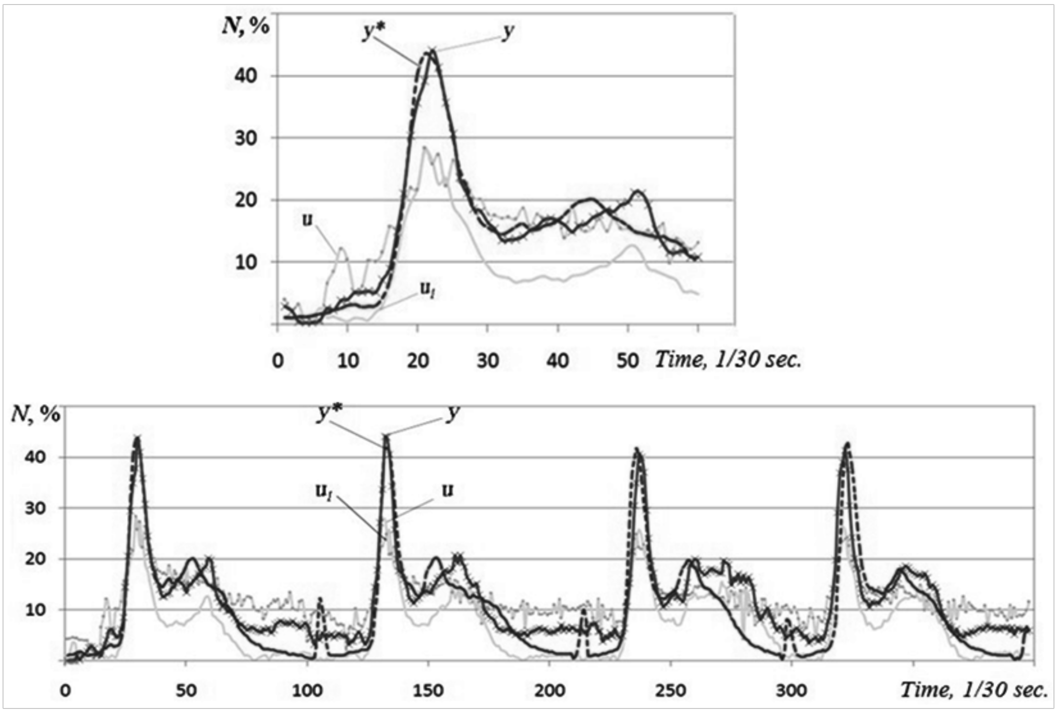

Fig. 9. EG Smoke Model with Two Inputs in Different Time Intervals: u - “white on the black” component; u_1 - “black on the white” component; *y** - test data; *y* - modeled data

When analyzing the content of the exhaust gas from the point of view of only black components, the proposed measurement method works as a filtration one, whereas taking into account the basis of black and whitish components, it is considered to be optical.

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